(12)

Technical Publication TP000025

PULSE CODE MODULATION TELEMETRY
Properties of Various Binary Modulation Types

(AIRTASK A6306302-054D-8W0604000, Work Unit A6302D-02)

By
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June 1984

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This report describes work accomplished under AIRTASK A6306302-054D-8W0604000, Range Instrumentation Development and Test, and Work Unit A6302D-02, Range Telemetry Support.

Mr. M. A. Beckmann, Head, Electronic Design Branch; Mr. E. L. Law, Task Coordinator; and Mr. D. F. Senecal, NAVAIR Special Programs Manager, have approved this report for publication.

Dr. K. I. LICHTI
Technical Director

Technical Publication TP000025

Published by . . . . Information Technology Office
Security classification . . . . UNCLASSIFIED
First printing . . . . 405 copies

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER TP000025	2. GOVT ACCESSION NO. AD-A147 214	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) PULSE CODE MODULATION TELEMETRY Properties of Various Binary Modulation Types		5. TYPE OF REPORT & PERIOD COVERED 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Eugene L. Law		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Pacific Missile Test Center Point Mugu, California 93042		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS AIRTASK A6306302-054D-8W0604000, Work Unit A6302D-02
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Air Systems Command Washington, DC 20361		12. REPORT DATE June 1984 13. NUMBER OF PAGES 134
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

PCM	Telemetry	Receiver bandwidth
PCM codes	Predetection recording	PSK
PCM recording	Bit error rate	
PCM/FM	Radio frequency spectra	
PCM/PM	Peak deviation	

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report describes the results of a study that was conducted to determine the properties of several binary pulse code modulation types. The topics addressed include:

1. Radio frequency spectral occupancy,
2. Bit error rate versus intermediate frequency signal-to-noise ratio in a bandwidth equal to the bit rate,
3. Peak carrier deviation,
4. Effect of filtering on data quality, and
5. Frequency and phase modulation.

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ACRONYMS AND ABBREVIATIONS

AC	Alternating current
AFC	Automatic frequency control
BER	Bit error rate
BIO-L, -M, -S	Biphase level, mark, space
BW	Bandwidth
CA	Constant amplitude
CD	Constant delay
CW	Continous wave
dB	Decibel
dBc	Decibel referred to carrier level
dBm	Decibel referred to 1 milliwatt
DC	Direct current
DET	Detector
DEV	Deviation
E_B	Signal energy per bit
ENPBW	Equivalent noise power bandwidth
erfc	Complementary error function
FM	Frequency modulation
FM/FM	Frequency modulation/frequency modulation
F/S	Filter and sample
GHz	Gigahertz
Hz	Hertz
I/D	Integrate and dump
IF	Intermediate frequency
IFM	Incidental frequency modulation
ips	Inches per second
IRIG	Inter Range Instrumentation Group
kb/s	Kilobits per second
kHz	Kilohertz
LIN	Linear
LTD	Limited
Mb/s	Megabits per second
MHz	Megahertz
MOD	Modulation
NRZ-L, -M, -S	Non-return-to-zero level, mark, space

ACRONYMS AND ABBREVIATIONS

PAM	Pulse amplitude modulation
PBK	Playback
PCM	Pulse code modulation
PLL	Phase-locked loop
PM	Phase modulation
PN	Pseudo noise
POST-D	Postdetection
PRED, PRE-D	Predetection
PREMOD	Premodulation
PSD	Power spectral density
PSK	Phase shift keying
RC	Resistance-capacitance
RCC	Range Commanders Council
RCD	Record
RF	Radio frequency
rms	Root mean square
SCO	Subcarrier oscillator
SNR	Signal-to-noise ratio
V	Volt
VCO	Voltage-controlled oscillator
VID	Video

TP000025
June 1984

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SUMMARY

This report describes the results of a study that was conducted to determine the properties of several binary pulse code modulation types. The topics addressed include:

1. Radio frequency spectral occupancy.
2. Bit error rate versus intermediate frequency signal-to-noise ratio in a bandwidth equal to the bit rate.
3. Peak carrier deviation.
4. Effect of filtering on data quality.
5. Frequency and phase modulation.

The major conclusions are:

1. Phase modulation yields the best data quality if wide bandwidths are available.
2. Non-return-to-zero level pulse code modulation/frequency modulation yields the best data quality if the bandwidth is narrow.
3. Non-return-to-zero pulse code modulation/frequency modulation has the narrowest spectral occupancy of the methods discussed in this report.
4. The receiver intermediate frequency bandwidth should not be wider than twice the predetection carrier frequency when predetection recording is used.

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INTRODUCTION

This report presents information on the performance of pulse code modulation/frequency modulation (PCM/FM), pulse code modulation/phase modulation (PCM/PM) and phase shift keying (PSK). The topics addressed include:

1. Radio frequency (RF) spectra.
2. Bit error rate (BER) versus predetection signal-to-noise ratio (SNR).
3. Peak carrier deviation.
4. Premodulation and receiver predetection filter selection.
5. Non-return-to-zero (NRZ) and biphase (BIO) level, mark, and space codes.
6. Predetection recording.
7. Receiver video filter selection.
8. Bit synchronizer bit detector selection.
9. Hybrid systems.

The purpose of this report is to provide the reader with information needed to choose the best modulation method, PCM code, premodulation filter bandwidth and type, receiver settings and recording method for a particular application.

Many methods exist for the transmission of telemetry data. This report will only discuss methods for the transmission of digital data. The Telemetry Group of the Range Commanders Council (RCC) has sponsored this study to compare the performance of these methods under simulated range conditions.

TEST SETUP

Tests were performed to characterize the performance of the various PCM modulation methods using standard telemetry equipment. The test setup is shown in figure 1. The PCM test set, root mean square (rms) voltmeter, spectrum analyzer and attenuator were under computer control. The receiver intermediate frequency (IF) SNR was measured with an unmodulated carrier at the highest IF SNR used in the test (attenuator set to 21 dB). The carrier was then modulated and the BER measured at each attenuator setting between 21 and 31 dB. The measured attenuation at each attenuator setting was then used to calculate the unmodulated carrier IF SNR at each attenuator setting. The measured receiver equivalent noise power bandwidth was used to convert the measured IF SNR to an SNR in a bandwidth equal to the bit rate. This normalizes the performance of the various modulation methods and bit rates.

BER REPEATABILITY AND ACCURACY

The BER data in this report were taken over intervals of 10^6 or 10^7 bits at low BERs. The test algorithm was such that if more than 2,000 errors were detected in a measurement interval, the next measurement interval was one-tenth as long. Figures 2 and 3 show the superposition of 21 consecutive BER tests with an initial interval of 10^6 bits. These figures show that the BER data repeatability is better than ± 0.2 dB for BERs higher than 10^{-4}. The data spread at a 10^{-5} BER (10 bit errors measured) is ± 0.4 dB for figure 2 and ± 0.5 dB for figure 3. The theoretical data spread is ± 0.3 dB for 95% of the values at a BER of 10^{-5} and a sample interval of 10^6 bits. The theoretical data spread is ± 0.1 dB for a BER of 10^{-4} and a sample interval of 10^6 bits. The theoretical data spread for a 10^{-5} BER and a sample interval of 10^7 bits is ± 0.13 dB.

The accuracy of the BER versus IF SNR in a bandwidth equal to the bit rate is also affected by the accuracy of the IF SNR and equivalent noise power bandwidth measurements. The accuracy of these measurements is estimated to be approximately ± 0.1 dB. Another major factor is test equipment performance, especially the telemetry receiver, demodulator, and PCM bit synchronizer. Slightly different values will be measured with different equipment.

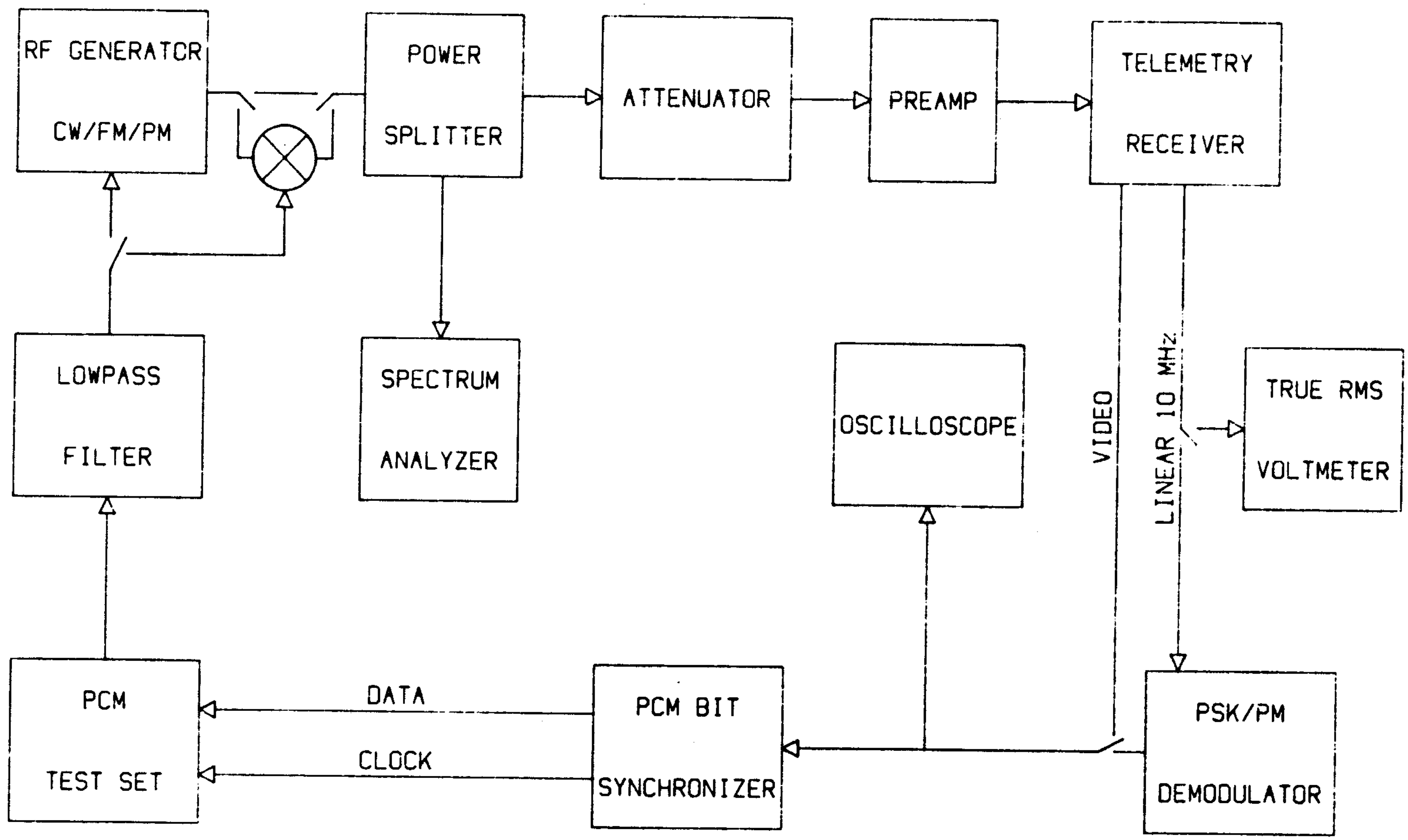

Figure 1. Test Setup.

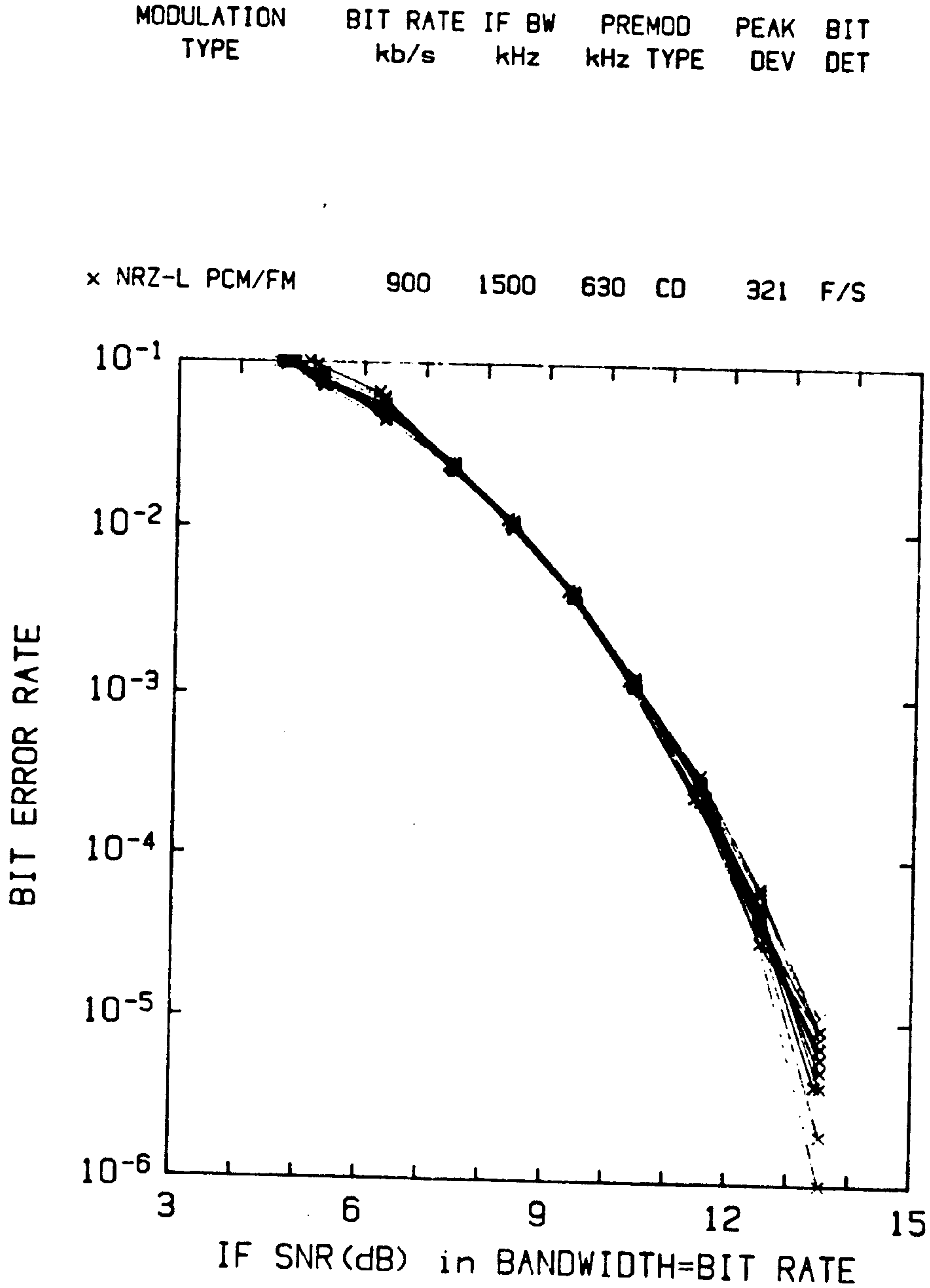

Figure 2. BER Repeatability PCM/FM.

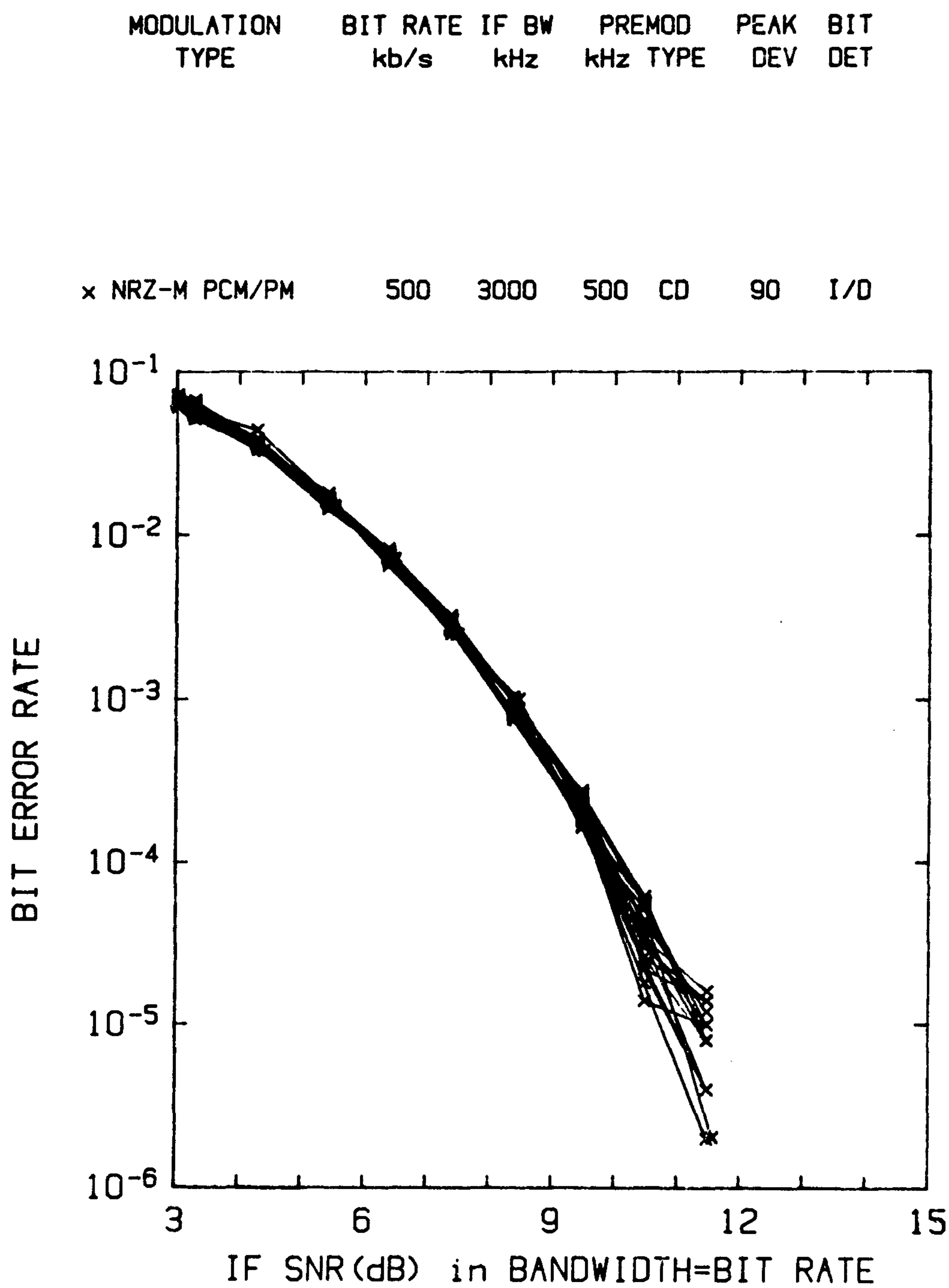

Figure 3. BER Repeatability PCM/PM.

NRZ PCM/FM

Introduction

Non-return-to-zero pulse code modulation/frequency modulation (NRZ PCM/FM) is a combined coding and modulation method used to send digital data over a transmission link. The method provides a shift in carrier frequency of x hertz (Hz) higher in frequency to represent one state of a binary signal (usually the ONE state) and a shift of x hertz lower in frequency to represent the other state (usually the ZERO state) of the binary signal. The most commonly used code for PCM/FM is the non-return-to-zero level (NRZ-L) code.[1] As the name, NRZ-L implies, the level of the modulation stays the same until the data changes state - that is, the level does not go to zero level between the data pulses.

The non-return-to-zero mark and space (NRZ-M and NRZ-S) versions are sometimes used when very long strings of either ones or zeros are expected in the data stream. If long streams of zeros (but not of ones) are expected in the data stream, then the NRZ-S coding method is used because it provides a transition for each zero in the data stream. The NRZ-M code is used to force transitions in the data stream when long strings of ones are expected in the data. The purpose for selecting a coding method which provides additional transitions is that the PCM bit synchronizer needs transitions to generate a reconstructed clock of the proper phase and frequency.

The NRZ-M and NRZ-S codes have the advantage of being polarity insensitive. This is, the PCM bit stream can be inverted and no change will occur in the output of the PCM bit synchronizer. A disadvantage of using these codes is that every isolated bit error causes the following bit to be in error also. Therefore, if one is going to use an error-correcting code in a system where the mark or space codes are used, the error correction encoding should be done after the data is converted to the mark or space code.

Several other techniques may be used to prevent the problems associated with long strings of ONES or ZEROS in the bit stream, they include: randomizing the data, adding an odd parity bit to words that have an odd number of data bits, and using biphase (Manchester) coding.

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[1]Secretariat, Range Commanders Council. Telemetry Standards. White Sands Missile Range, New Mexico, RCC, Sep 1980. (IRIG Standard 106-80).

Selection of Peak Deviation

The optimum peak deviation for NRZ PCM/FM is approximately 0.35 times the bit rate; i.e., a 1.0 megabit per second (Mb/s) bit stream should have a peak deviation of 350 kilohertz (kHz) and a peak-to-peak deviation of 700 kHz.[2,3,4,5] Most papers on the subject of PCM/FM deviation use peak-to-peak values (usually symbolized by an h) but, peak deviation is used in this document to keep PCM/FM consistent with FM/FM, PAM/FM, and PCM/PM where peak deviation is generally used to describe the amount of deviation. This optimum value of peak deviation is valid when using IF bandwidths (BWs) that are between 1 and 3 times the bit rate and for systems where the total incidental frequency modulation (IFM) is much smaller than the peak deviation. Incidental frequency modulation is defined as follows: the carrier deviation produced by frequency modulation when the modulating signals are not wanted and are internal to the RF signal source. Typical transmitter IFM specifications are 5 kHz peak and/or 2 kHz rms. Therefore, the minimum PCM/FM peak deviations should be 15 to 20 kHz; i.e., 3 to 4 times peak or 7.5 to 10 times rms. The actual minimum useable peak deviation is a function of the actual transmitter frequency stability and the receiving system frequency stability. It is noted, that, if the predetection bandwidth is wider than 3 times the bit rate, the optimum peak deviation may be greater than 0.35 times the bit rate. In addition, phase modulation may be preferable to frequency modulation for low bit rate systems. Data quality as measured by bit error rate (BER) performance is affected by the amount of carrier deviation and also the premodulation filter bandwidth, predetection IF filter, demodulator, and the bit detector characteristics.

When peak deviation is increased to a value of approximately 0.4 times the bit rate, the BER performance is typically degraded by a few tenths of a dB; i.e., at a BER of 1×10^{-5}, the degradation is in a range of 0.2 to 0.4 db (refer to figures 4 and 5). The major cause of degradation to signal quality is the additional attenuation introduced by the predetection IF filter at the peak deviation value; i.e., 0.4 dB more attenuation is present at $\pm$200 kHz than at $\pm$175 kHz (see figure 6). The result is that the instantaneous IF SNR is reduced by 0.4 dB, thus producing more bit errors in the data stream due to "pop" noise. Another cause of additional pops with

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[2]Kotelnikov, V. A. The Theory of Optimum Noise Immunity. Dover, New York, 1968.

[3]Gagliardi, R. M. Introduction to Communications Engineering. Wiley, New York, 1978.

[4]Tjhung, T. T., and Wittke, P. H. "Carrier Transmission of Binary Data in a Restricted Band," in IEEE Transactions on Communications, Vol. COM-18, pp. 295-304, August 1970.

[5]Cartier, D. E. "Limiter-Discriminator Detection Performance of Manchester and NRZ Coded FSK," in IEEE Transactions of Aerospace and Electronic System, Vol. AES-13, pp. 62-70, January 1977.

MODULATION TYPE	BIT RATE kb/s	IF BW kHz	PREMOD kHz TYPE	PEAK DEV	BIT DET
* NRZ-L PCM/FM	1000	1000	NONE	306	F/S
o NRZ-L PCM/FM	1000	1000	NONE	405	F/S
+ NRZ-L PCM/FM	1000	1000	NONE	350	F/S

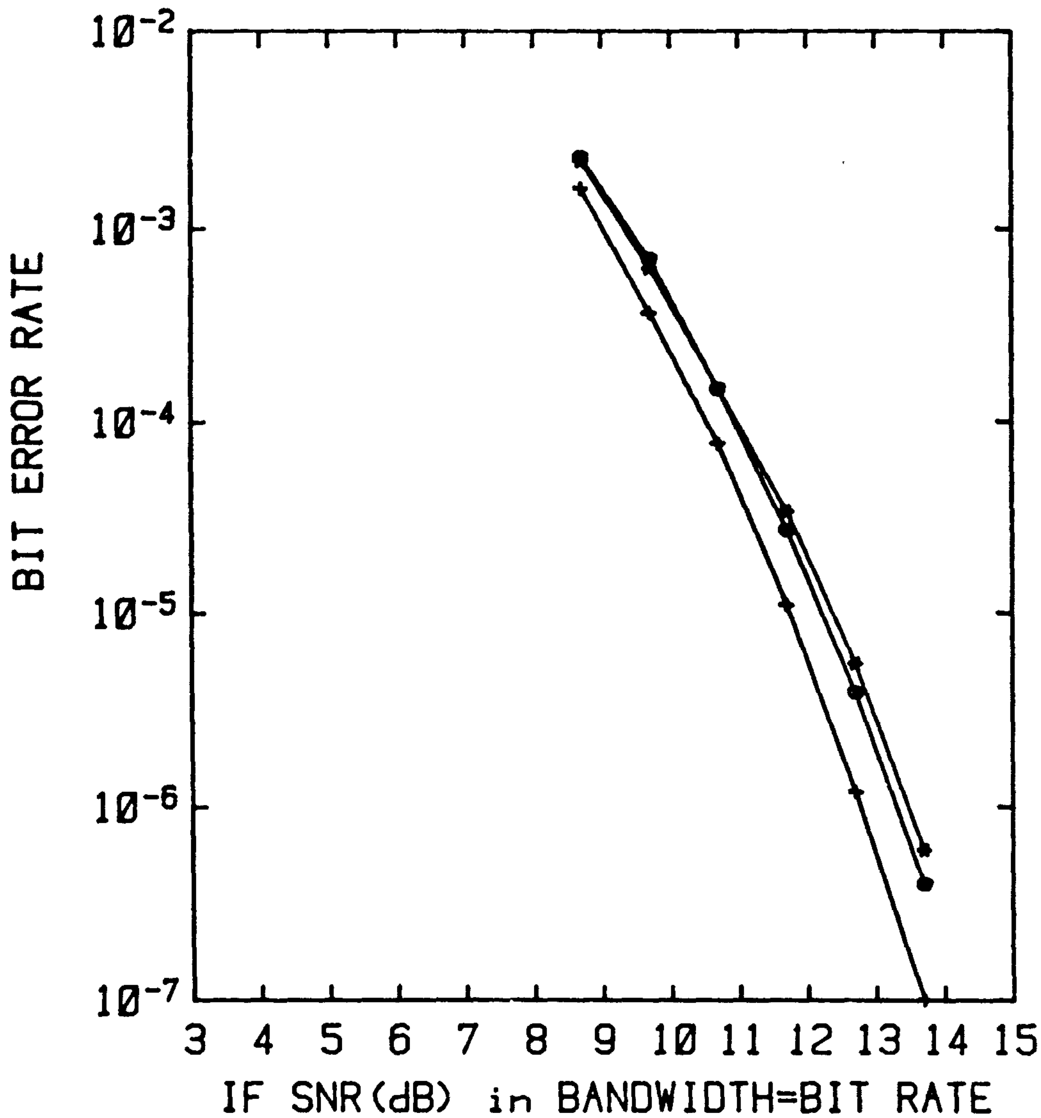

Figure 4. BER for Various Peak Deviations NRZ-L PCM/FM.

MODULATION TYPE	BIT RATE kb/s	IF BW kHz	PREMOD kHz	PREMOD TYPE	PEAK DEV	BIT DET
* NRZ-L PCM/FM	1000	1500	700	CD	200	F/S
0 NRZ-L PCM/FM	1000	1500	700	CD	400	F/S
× NRZ-L PCM/FM	1000	1500	700	CD	300	F/S
o NRZ-L PCM/FM	1000	1500	700	CA	357	F/S
+ NRZ-L PCM/FM	1000	1500	700	CD	357	F/S

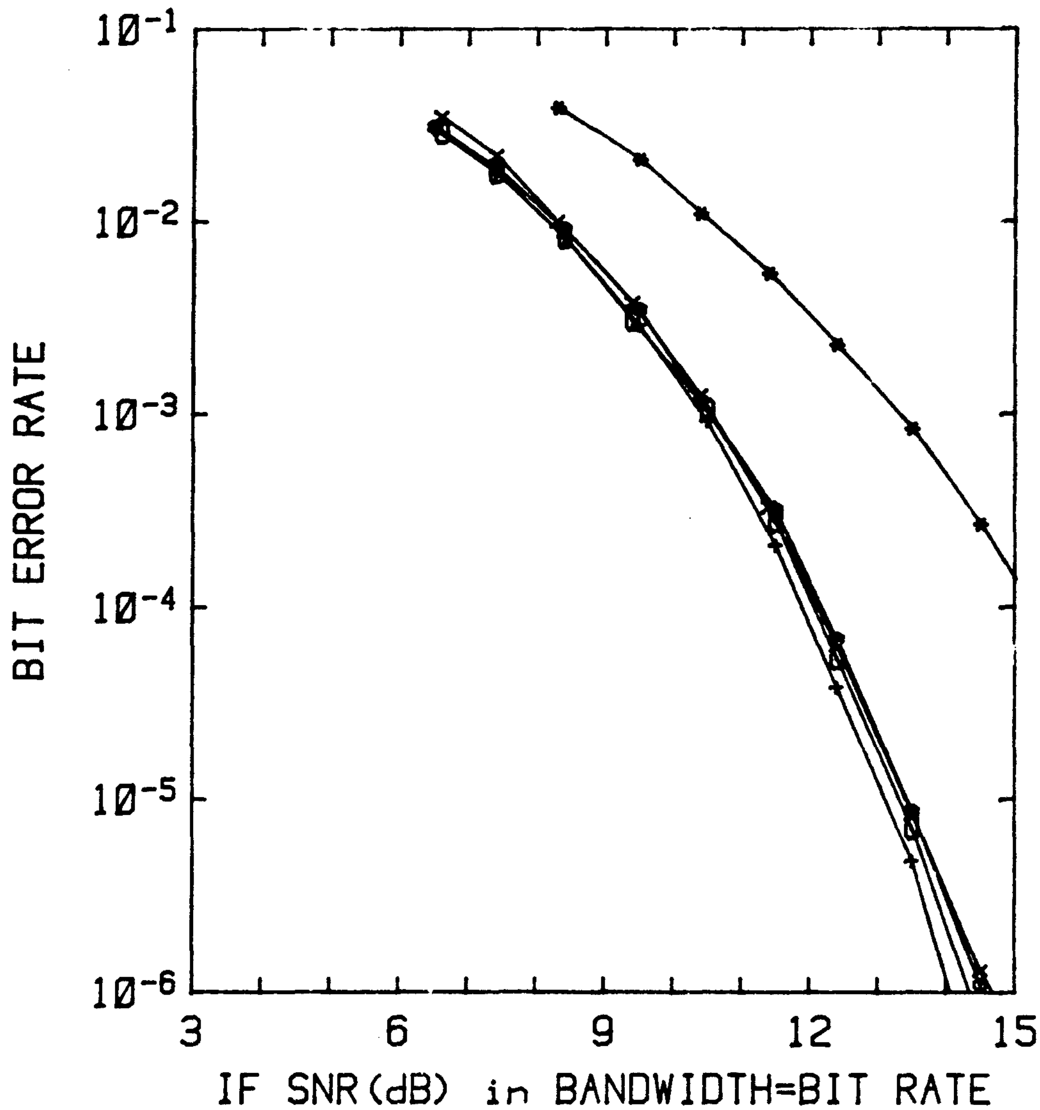

Figure 5. BER for Various Peak Deviations NRZ-L PCM/FM.

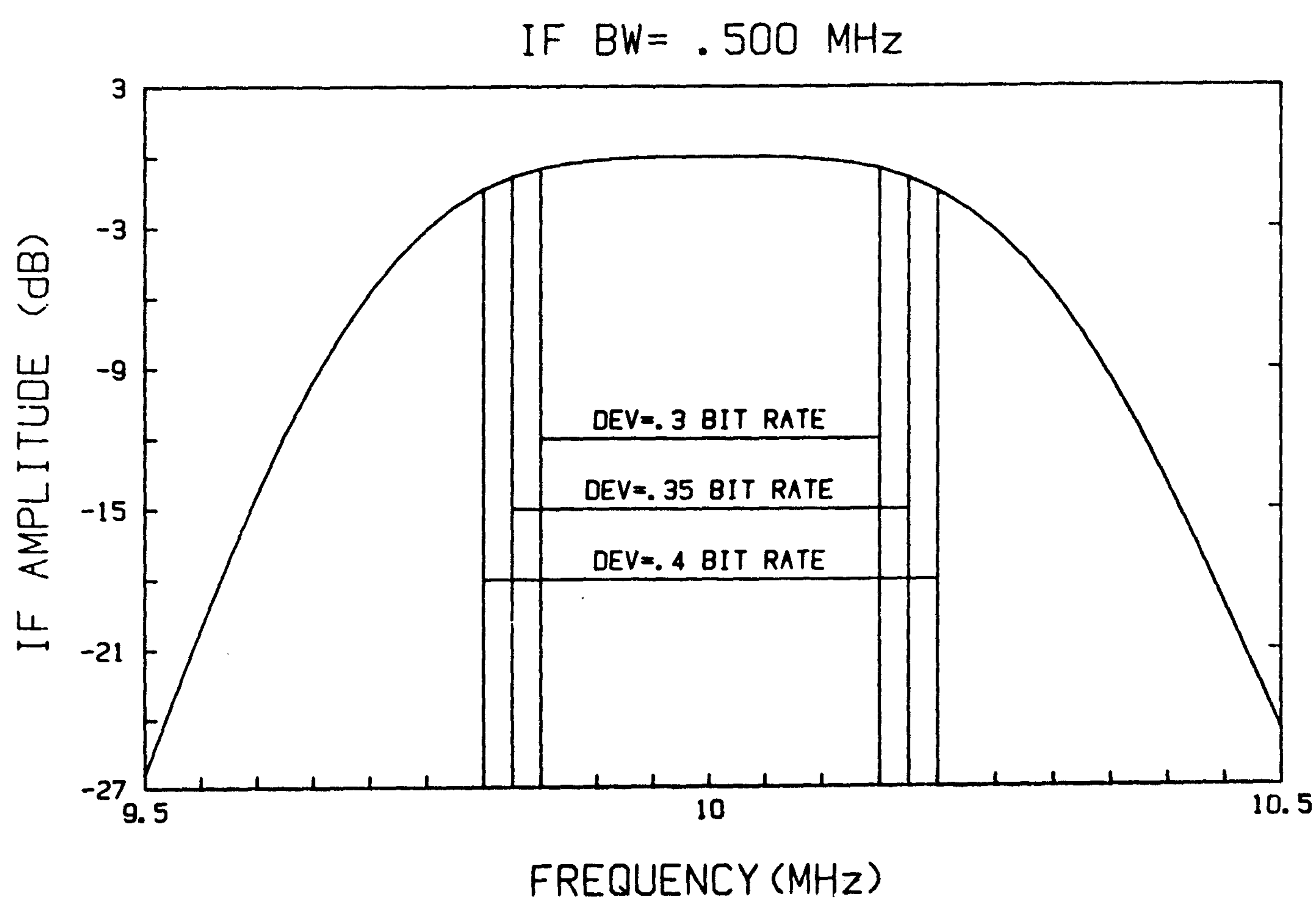

Figure 6. IF Filter Attenuation Versus Peak Deviation.

higher peak deviation is that the difference in frequency between the instantaneous signal frequency and the instantaneous noise frequency is usually larger. Therefore, the probability of the noise being larger than the signal for a long enough time interval to cause a pop is increased because the required time interval is inversely proportional to the difference in frequency. An additional possible cause of increased BER with increased deviation is that the phase linearity of the IF filter gets worse towards the band edges which produces more intersymbol interference.

However, the signal energy per bit is increased by 1.2 dB, (20 log (0.4/0.35)) which significantly reduces the number of bit errors due to fluctuation noise. Therefore, when the premodulation filter bandwidth is set to one-half the bit rate, it is expected that the degradation due to slight over deviation would be negligible. The reason the degradation is negligible is that the narrow premodulation filter bandwidth reduces the amplitude of single bits of either polarity, thus increasing the susceptability to the effects of fluctuation noise. Therefore, with an IF bandwidth equal to the bit rate and a premodulation filter bandwidth equal to one-half the bit rate, fluctuation noise is the major cause of bit errors.

In the case where the peak deviation is decreased to a value corresponding to approximately 0.3 times the bit rate, the bit error performance is typically degraded by approximately 0.6 dB at a BER of 1×10^{-5} (with the predetection IF bandwidth set equal to the data bit rate). The reason for this degradation is that the signal energy per bit is reduced by 1.3 dB, 20 log (0.3/0.35), which has the effect of significantly increasing the number of bit errors due to fluctuation noise. This increase in bit errors more than compensates for the decrease in bit errors resulting from pop noise, because of decreased predetection IF attenuation (0.4 dB as shown in figure 6).

Decreasing the peak deviation by 3 dB and 6 dB causes an increase in BER of 2.3 and 5.2 dB at a BER of 10^{-5}. This is illustrated in figure 7. Under the following conditions: BER = 10^{-5}, IF BW = 1.4 x bit rate, $\Delta f = 0.35$ times bit rate and premodulation filter bandwidth = 0.7 times bit rate, approximately one-third of the errors are due to fluctuation noise and two-thirds to pop noise. Increasing the deviation rapidly increases the errors due to pop noise (a peak deviation of 0.7 times the bit rate degrades the data quality by 4 to 6 dB when the IF bandwidth is equal to the bit rate), while decreasing the deviation rapidly increases the errors due to fluctuation noise. The noise at the output of an FM demodulator is discussed in more detail in appendix A.

Selection of Premodulation Filter

The best premodulation filter is the widest linear phase filter which allows the RF spectral occupancy requirements to be met. A low pass filter bandwidth (-3 dB) having a value that is equal to or greater than 0.7 times the bit rate will not cause a significant increase in the bit error rate. Table 1 shows the relationship between several premodulation filters and the IF SNR in a bandwidth equal to the bit rate required to achieve a BER of 1×10^{-5} using two different IF bandwidths. The test conditions for the data shown in table 1 include: A bit rate of 500 kilobits per second (kb/s), a

MODULATION TYPE	BIT RATE kb/s	IF BW kHz	PREMOD kHz	PREMOD TYPE	PEAK DEV	BIT DET
o NRZ-L PCM/FM	700	1000	500	CD	123	F/S
+ NRZ-L PCM/FM	700	1000	500	CD	173	F/S
* NRZ-L PCM/FM	700	1000	500	CD	245	F/S

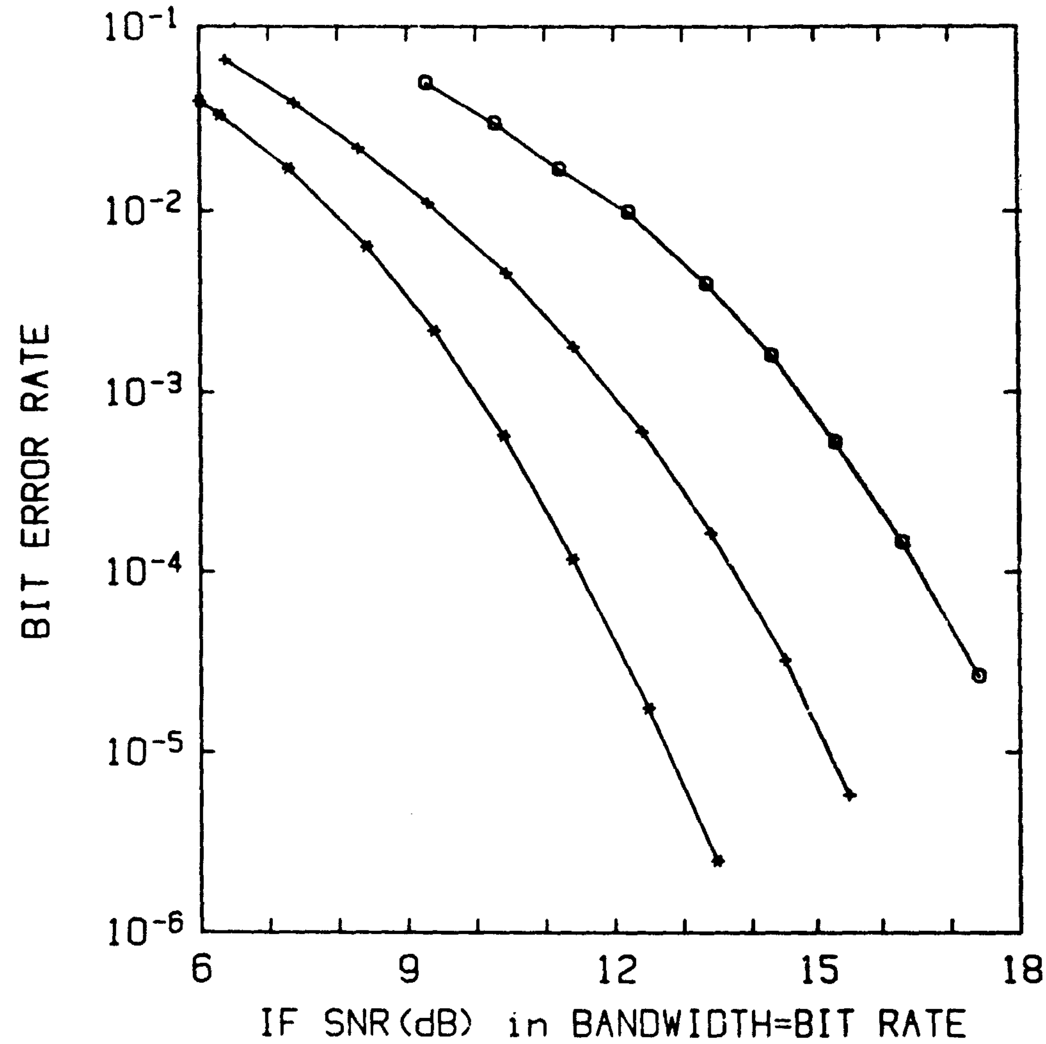

Figure 7. BER for Peak Deviation=.175, .25 and .35 Bit Rate.

peak deviation of 178 kHz, an NRZ-L code, and a filter and sample (F/S) bit detector. The bit error rates achieved while using linear phase filters were repeatedly as good or better than the bit error rates achieved while using constant amplitude (CA) filters having the same 3 dB bandwidth.

Table 1. SNR (dB) for 10^{-5} BER for Various Premodulation Filters.

500 kb/s NRZ-L PCM/FM
Peak Deviation = 175 kHz

IF Bandwidth (kHz)	Premodulation Filter Bandwidth (kHz)	Premodulation Filter Type	SNR (dB) for BER of 1×10^{-5}
500	None		11.9
500	500	CD	11.9
500	500	CA	11.9
500	350	CD	12.1
500	250	CD	12.7
500	250	CA	12.9
1000	None		13.7
1000	500	CD	13.7
1000	500	CA	13.7
1000	250	CD	13.9
1000	250	CA	14.3

Figures 8 through 11 show the PCM wavetrains which result when an NRZ-L signal is filtered at the bit rate and one-half the bit rate using 5-pole constant delay (CD) and constant amplitude low pass filters.

DC Component Versus AC Coupling

The level of the DC component contained in an NRZ-L data stream can vary over a wide range: from a level of approximately zero volt direct current (V DC) with randomized data to a level equal to 100% of the pulse amplitude when long strings of data without a transition are encountered. Therefore, NRZ-L signals are never to be AC-coupled when used to frequency-modulate a voltage-controlled oscillator (VCO). The Inter-Range Instrumentation Group (IRIG) Standards prohibit the use of AC coupling of NRZ-L signals in the statement that "frequency deviation from the carrier shall be the same for each occurence of the same level." The reason for avoiding alternating current (AC) coupling is that it forces the average value to be zero V DC. When the number of ones and zeros is nearly equal over any short time interval, the frequency for a one will be $f_0 + x$ and the frequency for a zero will be $f_0 - x$. However, if the ratio of ones to zeros changes to three ones to each zero and the signal is AC-coupled, then the frequency for a one will be $f_0 + x/2$ and the frequency for a zero will be $f_0 - 3x/2$. The lack of balance between the ones and zeros can cause major data degradation problems due to the effects of signal attenuation in the final IF filter of the receiver or in any other bandwidth-limited device in the

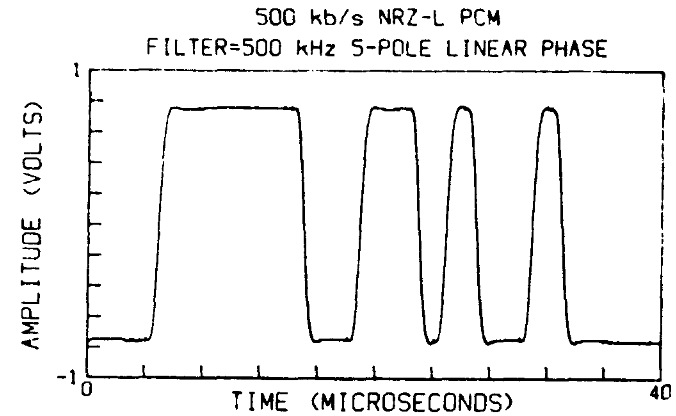

Figure 8. NRZ-L Signal with PREMOD Filter=Bit Rate (CD).

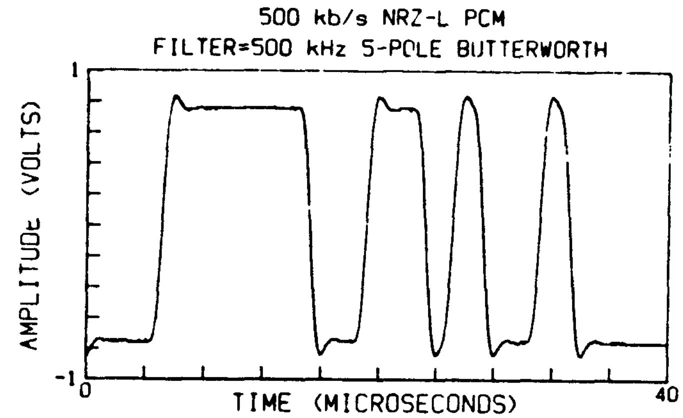

Figure 9. NRZ-L Signal with PREMOD Filter=Bit Rate (CA).

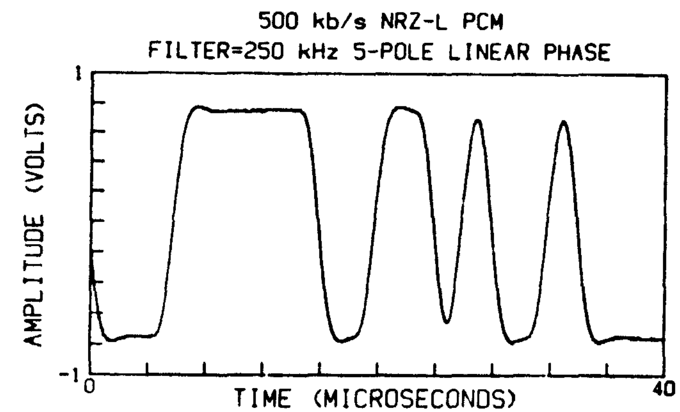

Figure 10. NRZ-L Signal with PREMOD Filter=Bit Rate/2 (CD).

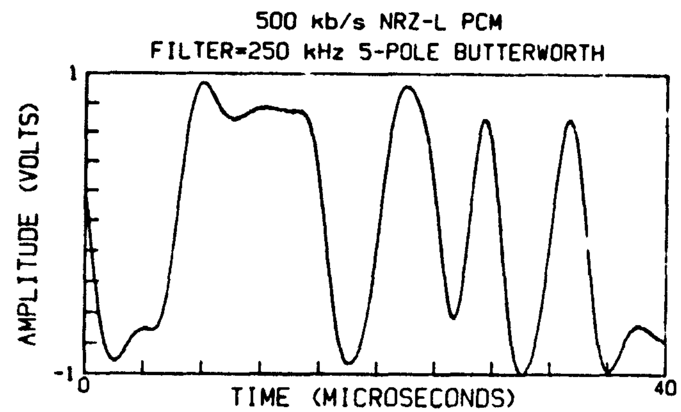

Figure 11. NRZ-L Signal with PREMOD Filter=Bit Rate/2 (CA).

telemetry system; i.e., such as an analog microwave link because the level that is present least often appears to be deviated farther from the carrier, as is illustrated in figure 12. In figure 12, the DC-coupled frequencies for ones and zeros are attenuated by 0.9 dB by the receiver IF filter. Assume the BER is 10^{-5}. Increasing the signal by 0.8 dB decreases the BER to 1.6×10^{-6} and decreasing the signal by 2.8 dB increases the BER to 10^{-3}. Therefore, the BER for the AC-coupled signal would be:

$$3/4\ (1.6 \times 10^{-6}) + 1/4\ (10^{-3}) = 2.5 \times 10^{-4}.$$

The RF power would have to be increased by 1.9 dB to decrease the BER to 10^{-5}. Therefore, the data quality has been degraded by 1.9 dB by AC-coupling the signal. The degradation would be greater if the ratio of ones to zeros (or vice versa) was larger than 3 to 1. An additional problem encountered when using AC coupling is that the energy associated with each bit in a long string of data bits without transitions is less than the energy in the previous bit because of the decay due to the resistance-capacitance (RC) time constant. Therefore, NRZ signals should never be AC-coupled unless some sort of positive control exists over the ratio of ones to zeros (the ratio should be one). One method of achieving this control is to randomize the NRZ signal. However, most randomization techniques cause an increase in the BER. Adding a parity bit does not provide sufficient control.

Selection of Receiver IF Bandwidth

When using a peak deviation value corresponding to approximately 0.35 times the bit rate, the optimum IF bandwidth is equal to the bit rate. This is illustrated in figure 13. Comparing IF SNRs in a bandwidth equal to the bit rate, we find that 500 kb/s (IF bandwidth/bit rate = 1) performs 0.2 dB better than 400 kb/s (IF bandwidth/bit rate = 1.25) and 1 dB better than 600 kb/s (IF bandwidth/bit rate = 0.83) at a BER of 10^{-4}. At lower BERs, the 600-kb/s data rapidly degrades relative to the other bit rates because of the excessive filtering of the bit stream. It should be noted that if we were receiving both 400 kb/s and 500 kb/s through 500-kHz IF filters, the 400-kb/s data would achieve a 10^{-4} BER with 0.8 dB less actual IF SNR (or less transmitted power). Using an IF bandwidth equal to 1.5 times the bit rate causes a degradation of approximately 0.7 dB, and a bandwidth of twice the bit rate causes a degradation of approximately 1.8 dB. It is noted that when an IF bandwidth with a value equal to the bit rate is used, the receiver tuning becomes very critical. The effect of improper tuning is illustrated in figure 14. Tuning problems can be encountered due to transmitter drift, doppler shift, receiver drift, and ground station operator error. Small tuning errors can produce relatively large increases in the bit error rate. The reason for the increase in bit error rate is that the slopes of the IF bandpass filter roll off quite rapidly outside of the receiver passband; thereby attenuating the signal when the receiver is detuned. The following example points out the effects of receiver detuning: For a signal at 500 kb/s data rate passing through a 500-kHz IF bandwidth, the penalty is approximately 1 dB for 50 kHz of detuning and 2.5 dB for 100 kHz of detuning. For comparison, the penalty for using a 750-kHz IF bandwidth is approximately 0.7 dB, and a 1.0-MHz IF bandwidth is approximately 1.8 dB. The loss with a 100-kHz detuning error and a 750-kHz

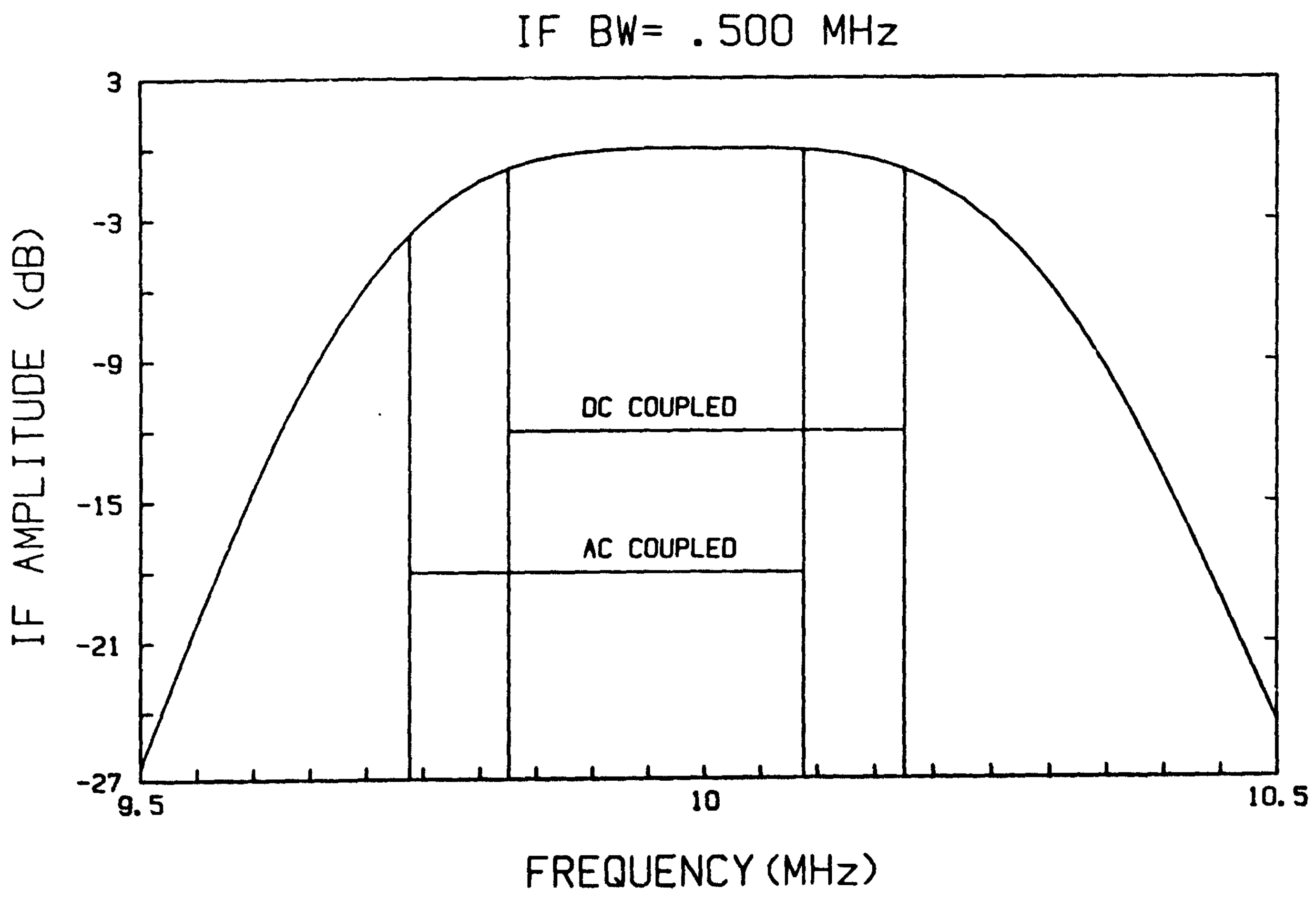

Figure 12. Effect of AC Coupling on NRZ-L in 500 kHz IF BW.

MODULATION TYPE	BIT RATE kb/s	IF BW kHz	PREMOD kHz	PREMOD TYPE	PEAK DEV	BIT DET
0 NRZ-L PCM/FM	600	500	500	CD	210	F/S
o NRZ-L PCM/FM	500	500	500	CD	175	F/S
* NRZ-L PCM/FM	400	500	500	CD	140	F/S

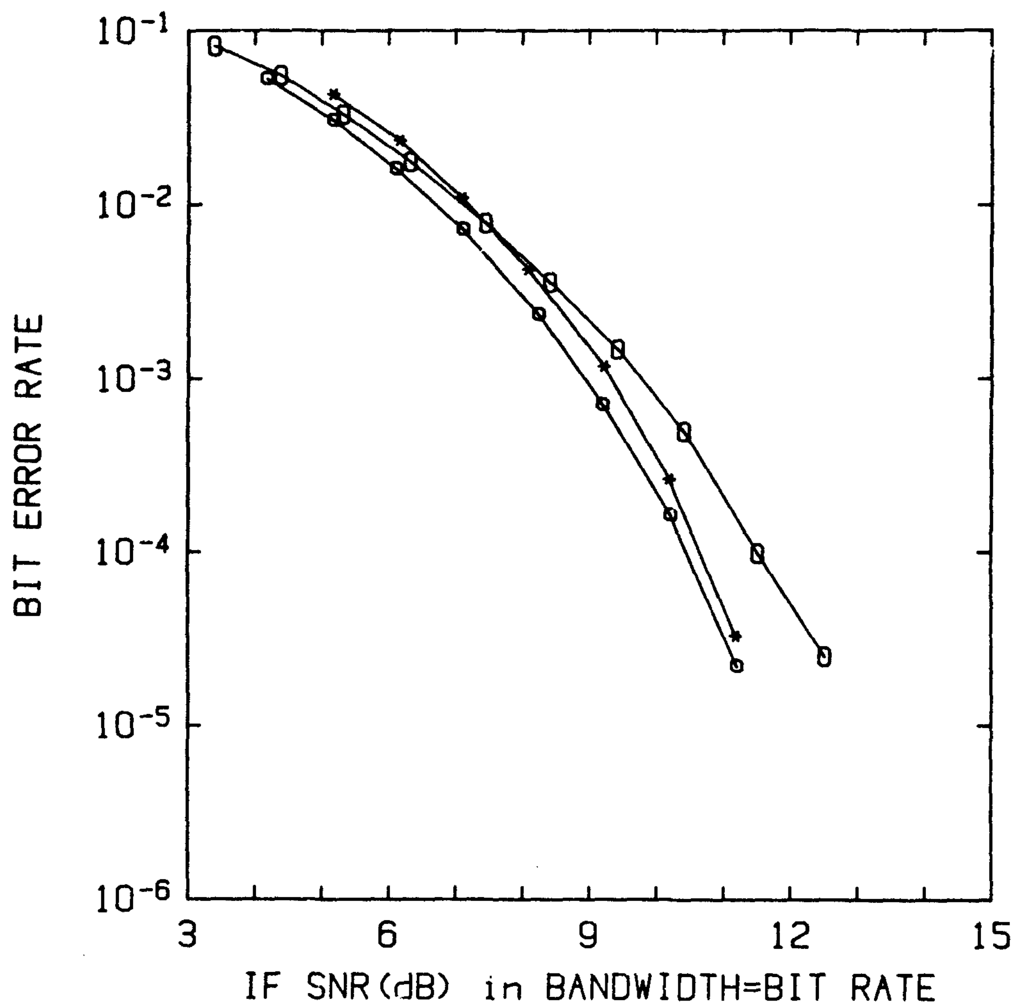

Figure 13. BER for 400, 500 and 600 kb/s NRZ-L in 500 kHz IF BW.

MODULATION TYPE	BIT RATE kb/s	IF BW kHz	PREMOD kHz	TYPE	PEAK DEV	BIT DET
* NRZ-L PCM/FM -100	1000	1000CA	700	CD	357	F/S
x NRZ-L PCM/FM+100	1000	1000CA	700	CD	357	F/S
o NRZ-L PCM/FM AFC	1000	1000CA	700	CD	357	F/S
+ NRZ-L PCM/FM	1000	1000CA	700	CD	357	F/S

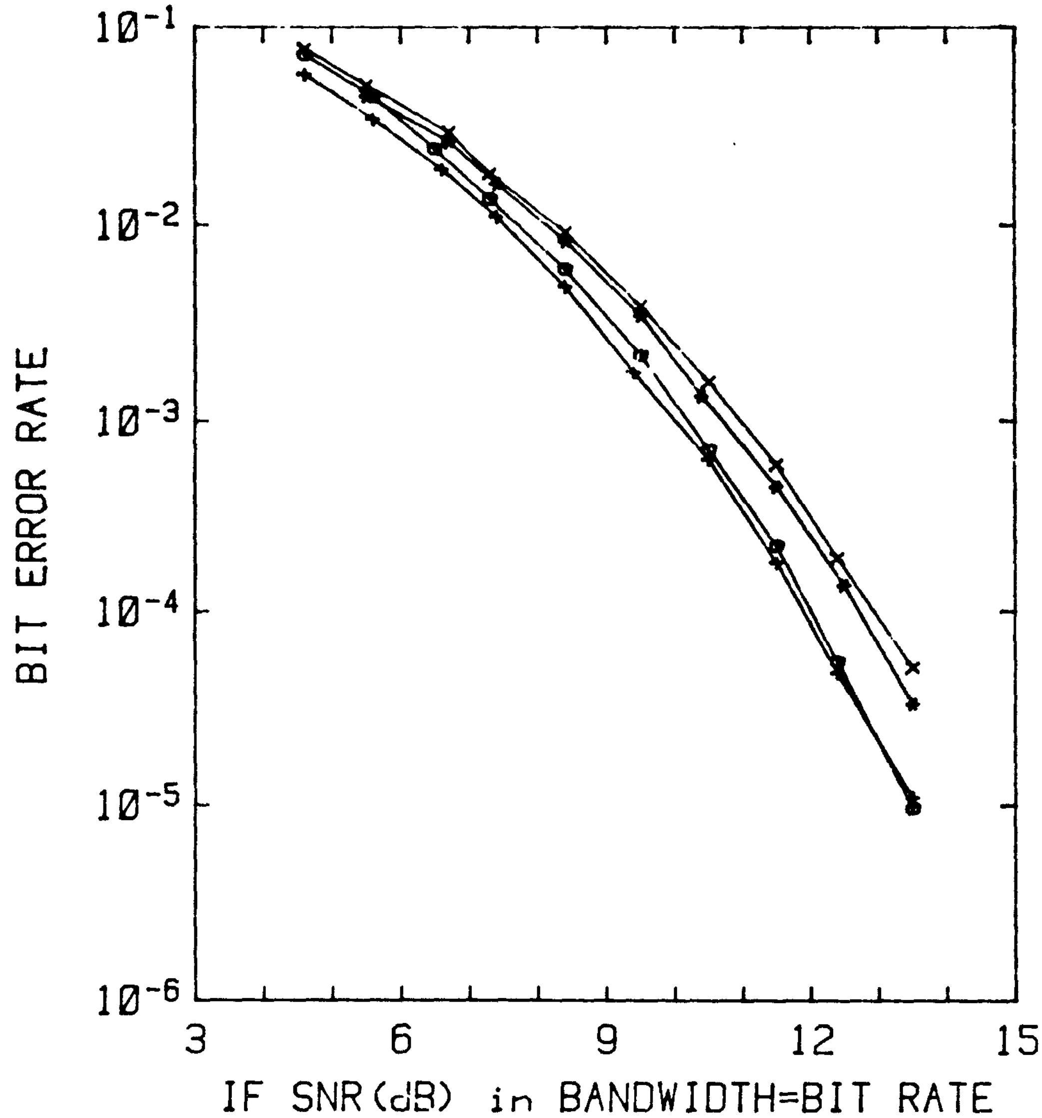

Figure 14. BER with AFC and 100 kHz Detuning.

IF is approximately 1.0 dB and with a 1.0-MHz IF is approximately 0.6 dB. The actual losses in a given receiver depend on the amplitude and phase characteristics of the receiver filters. The amplitude characteristic of some receiver IF filters is not symmetrical about the center frequency. This causes excessive bit errors in one of the two states of the PCM signal.

A second area of concern associated with using receiver IF bandwidths set equal to the bit rate is that many receiver IF filters provide poor phase performance in the vicinity of their upper and lower band edges. Degraded phase performance can produce intersymbol interference and distorted bit symbol waveforms resulting in an increase in the bit error rate; especially at the lower bit error rates. Signal-to-noise ratio penalties of approximately 1 dB (0.7 to 1.4 dB) are typical at bit error rates of 1×10^{-5} with an IF bandwidth set to a value equal to the bit rate when a linear phase IF filter is not used. The penalty for using a non-linear phase IF filter decreases at higher bit error rates and for IF bandwidths which are set wider than a value equal to the bit rate because the bit error rate is dominated by pop noise under these conditions.

When PCM/FM signals are predetection-recorded, the receiver IF bandwidth should be set wider than the bit rate. Two major reasons for selecting the wider IF bandwidths when using predetection recording techniques are: (1) The effective filtering includes not only the receiver bandpass filter, but also the predetection downconverter, the magnetic tape recorder/reproducer, and the predetection filter in the demodulator; (2) The selection of the wider IF filter provides the means for recording the signal with a minimum amount of degradation. It is extremely difficult to recover data which has been degraded through excessive filtering prior to recording on magnetic tape; however, it is relatively simple to filter out excessive out-of-band noise which is recorded on the magnetic tape. It is to be noted that the receiver bandwidth should never be wider than approximately two times the predetection carrier frequency. Extremely wide IF bandwidths should not be used because the noise frequency components will fold-over around the zero hertz origin and back into the data frequencies. The result is that, when using extremely wide IF filter bandwidths, a degradation of 3 dB in the SNR could occur.

The bit error rate for a given unmodulated carrier IF SNR decreases as the IF bandwidth is increased. This is illustrated in figure 15. The bit error rate versus IF SNR for IF bandwidths wider than 3 times the bit rate is nearly the same because the instantaneous signal suffers very little attenuation due to IF filtering. Most receiver IF filters are quite flat over the middle 25% of their 3-dB bandwidth. However, if one plots the BER versus IF SNR in a bandwidth equal to the bit rate (see figure 16), one can readily see that the use of wide IF bandwidths greatly degrades the data quality. The use of an IF bandwidth equal to three times the bit rate requires 3 to 3.5 dB more IF SNR in a bandwidth equal to the bit rate than does the use of an IF bandwidth equal to the bit rate. This is equivalent to doubling the transmitted power. The use of an IF bandwidth equal to 1.5 times the bit rate usually causes a degradation of less than 1 dB. This is illustrated in figure 17.

MODULATION TYPE	BIT RATE kb/s	IF BW kHz	PREMOD kHz	PREMOD TYPE	PEAK DEV	BIT DET
0 NRZ-L PCM/FM	500	3000	350	CD	178	F/S
+ NRZ-L PCM/FM	500	1500	350	CD	178	F/S
o NRZ-L PCM/FM	500	1000	350	CD	178	F/S
* NRZ-L PCM/FM	500	500	350	CD	178	F/S

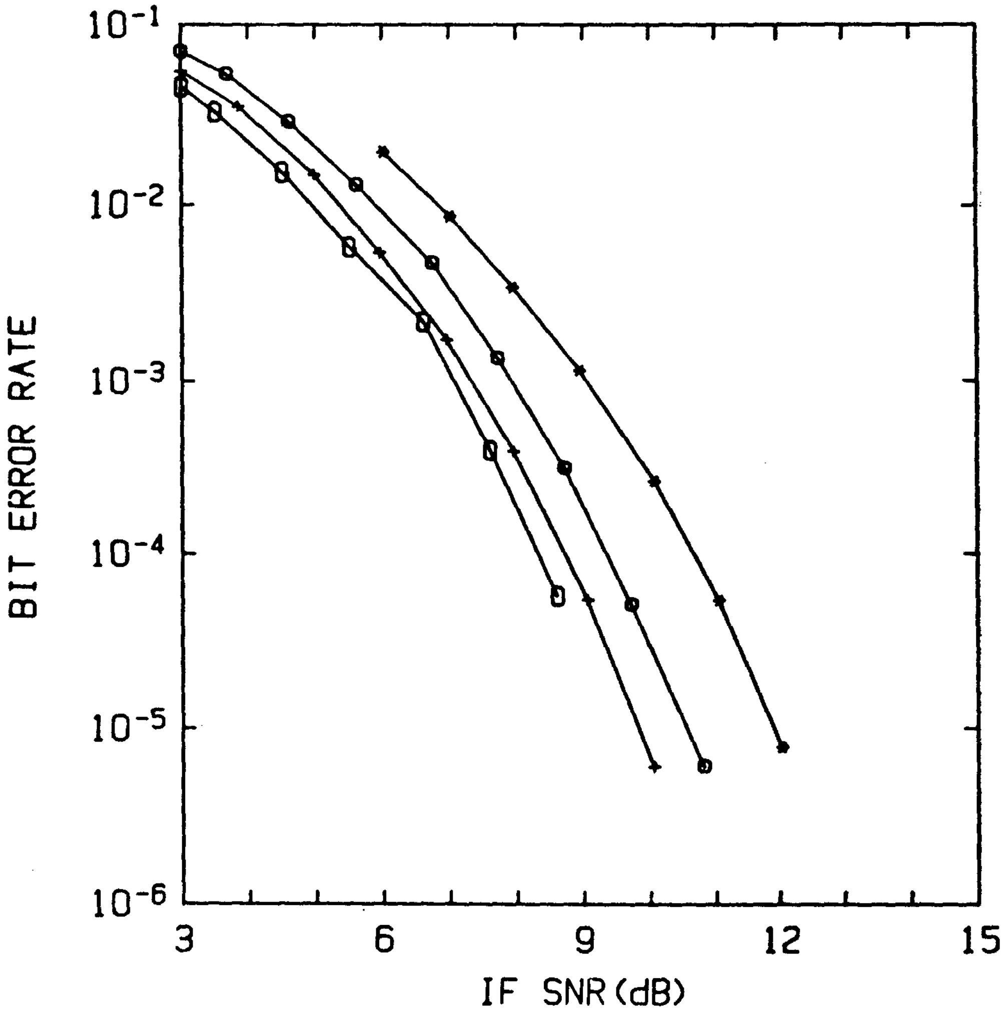

Figure 1[illegible]. BER with IF BW=1, 2, 3 and 6 Times Bit Rate (NRZ-L).

MODULATION TYPE	BIT RATE kb/s	IF BW kHz	PREMOD kHz	TYPE	PEAK DEV	BIT DET
0 NRZ-L PCM/FM	500	3000	500	CD	178	F/S
+ NRZ-L PCM/FM	500	1500	500	CD	178	F/S
o NRZ-L PCM/FM	500	1000	500	CD	178	F/S
* NRZ-L PCM/FM	500	500	500	CD	178	F/S

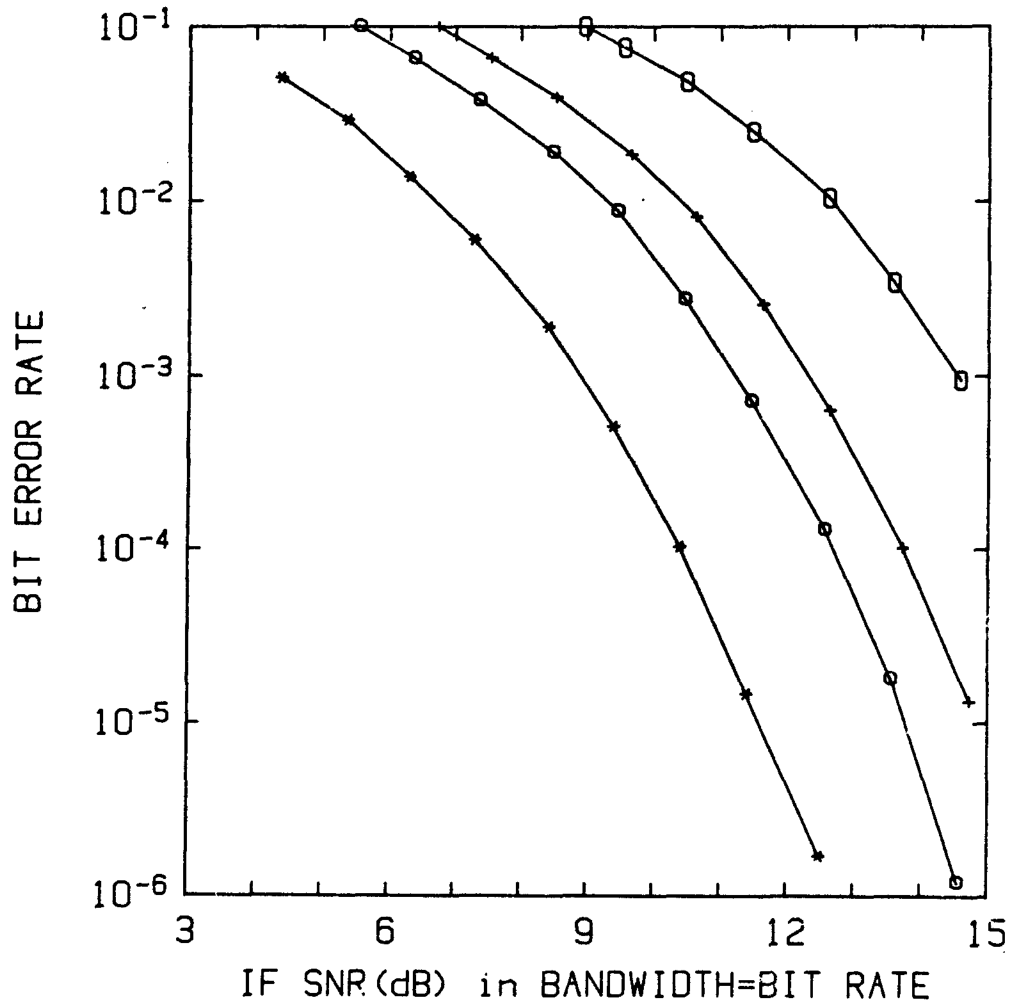

Figure 16. BER with IF BW=1, 2, 3 and 6 Times Bit Rate (NRZ-L).

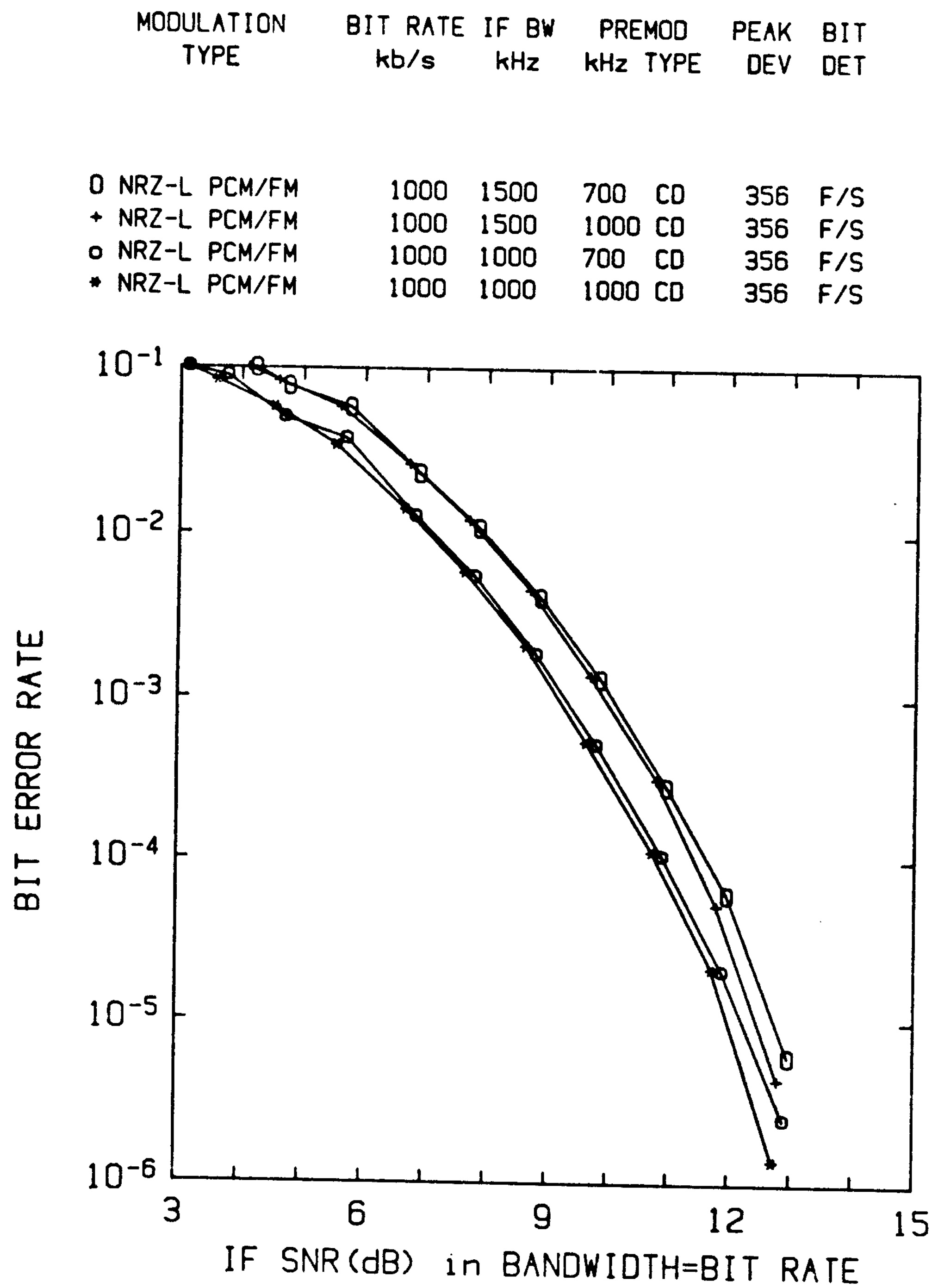

Figure 17. BER with IF BW=1 and 1.5 Times Bit Rate (NRZ-L).

Selection of Demodulator Video Bandwidth

The demodulator video bandwidth should not be set to a value which is less than one-half the bit rate. The preferred choice is usually a value which is between 0.7 and one times the bit rate; that is, for a 700-kb/s bit rate, the video bandwidth would be set to either 500 or 750 kHz. Note that filtering of the demodulated bit stream is also performed by the bit synchronizer. The use of narrow demodulator video filters, that is, less than 0.7 times the bit rate, will have the effect of making the PCM bit stream look "cleaner" to the eye, but may degrade the data quality. The reason being that the amplitude of the single bits is reduced more than the noise components. One exception does exist, if the bit synchronizer does not include a filter, but rather only samples the incoming data bit stream, the receiver video filter should be set to approximately 0.5 times the bit rate. The effect of video filtering is illustrated in figures 18, 19, and 20.

Selection of PCM Bit Synchronizer Bit Detector

The use of a filter and sample (F/S) bit detector in the bit synchronizer system is usually the best choice for NRZ PCM/FM data. The only exceptions to the recommended filter and sample detector are in applications involving either excessive or very minimal filtering of the data. In the case involving excessive filtering of the PCM signal prior to the PCM bit synchronizer, a sample bit detector may provide the best results; however, most modern bit synchronizer systems do not provide a sample bit detector as an option. In the case of an essentially unfiltered PCM data stream, the integrate and dump (I/D) bit detector may provide improved performance over that of the sample bit detector selection. However, the difference in performance is nearly insignificant because most of the bit errors are the result of noise pops under the conditions involving a wide IF bandwidth relative to the bit rate and essentially no other filtering.

RF Spectra

The measured RF spectrum of pseudo-random NRZ PCM/FM data using a peak deviation equal to 0.356 times the data bit rate (premodulation filter not used) is shown in figure 21. The frequency scale is relative to the center frequency for all RF spectral plots in this report. Approximately 91% of the spectral power shown in figure 21 is contained in a bandwidth equal to the bit rate. The bandwidth containing 99% of the power is 1.42 MHz. This is equal to 1.78 times the bit rate. This value is quite close to the calculated value of 1.8 times the bit rate for rectangular NRZ PCM/FM with peak deviation equal to 0.35 times the bit rate listed by Korn.[6] The RF spectra for pseudo-random NRZ PCM/FM with peak deviation values corresponding to 0.1, 0.175, 0.25, 0.356, 0.42, 0.5, 0.71, and 1.0 times the bit rate are presented in figures 22 through 29, respectively. The

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[6]Korn, I. "Error Probability and Bandwidth of Digital Modulation," in IEEE Transactions on Communications, Vol. COM-28, pp. 287-290, February 1980.

MODULATION TYPE	BIT RATE kb/s	IF BW kHz	PREMOD kHz	PREMOD TYPE	VIDEO kHz	BIT DET
× NRZ-L PCM/FM	1000	1000	1000	CD	500	I/D
X NRZ-L PCM/FM	1000	1000	1000	CD	500	F/S
o NRZ-L PCM/FM	1000	1000	500	CD	500	F/S
* NRZ-L PCM/FM	1000	1000	500	CD	1000	F/S

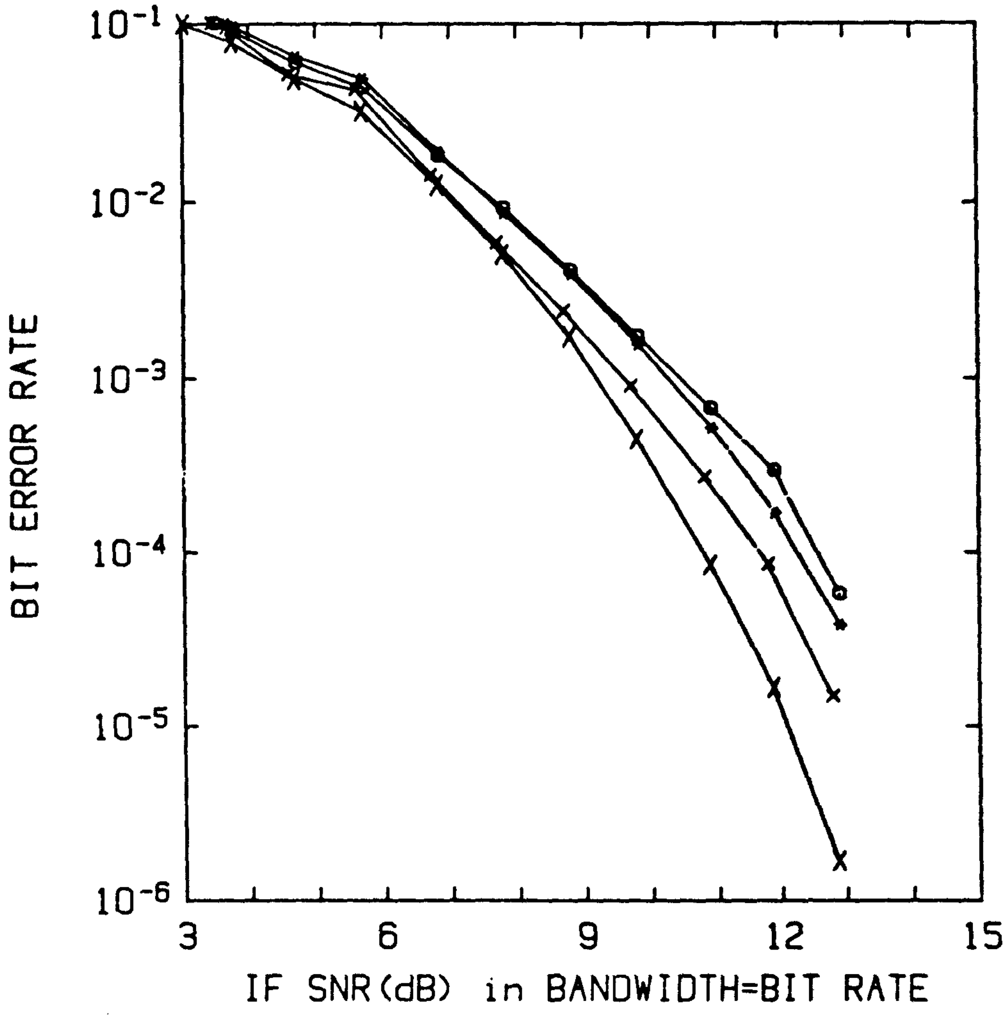

Figure 18. BER with Video and PREMOD BWs=0.5 and 1 Times Bit Rate.

MODULATION TYPE	BIT RATE kb/s	IF BW kHz	PREMOD kHz	PREMOD TYPE	VIDEO kHz	BIT DET
X NRZ-L PCM/FM	1000	1000	700	CD	500	F/S
o NRZ-L PCM/FM	1000	1000	700	CD	750	F/S
* NRZ-L PCM/FM	1000	1000	700	CD	1000	F/S

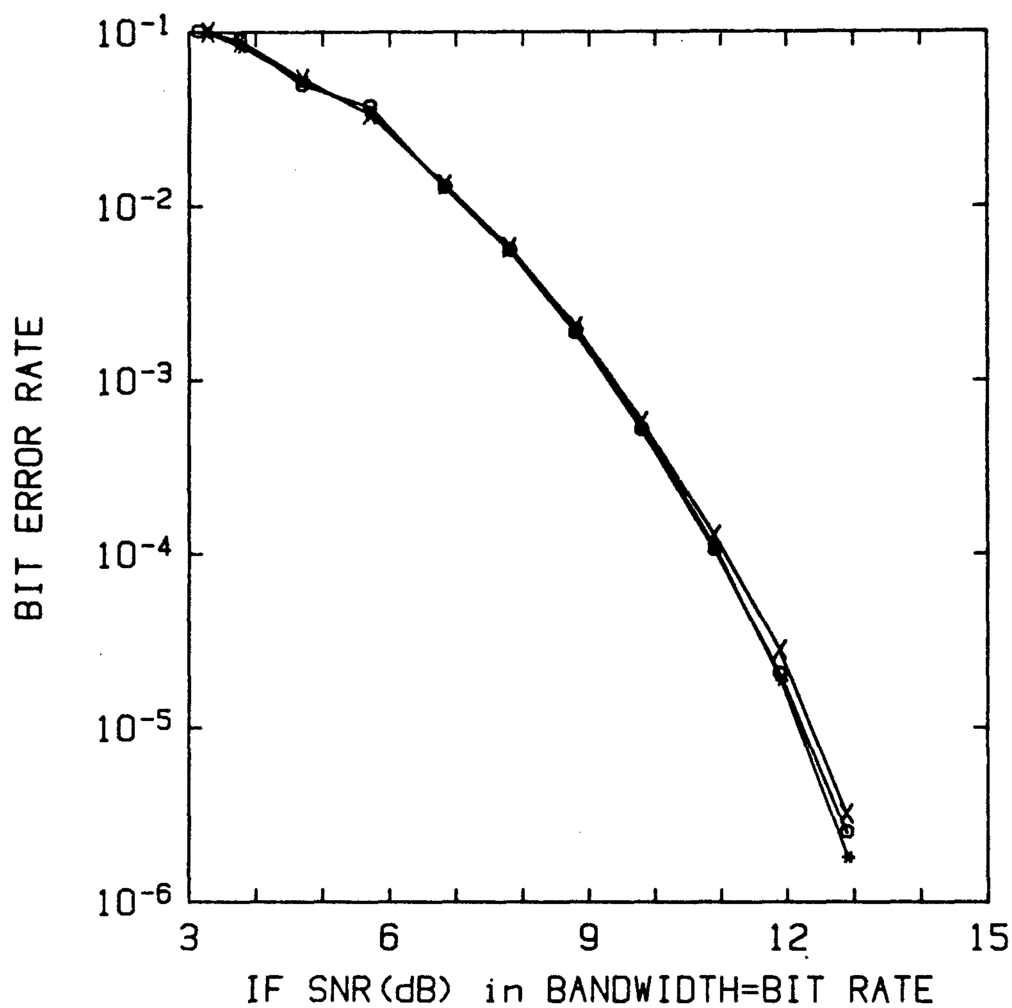

Figure 19. BER with Video BW=0.5, 0.75 and 1 Times Bit Rate.

MODULATION TYPE	BIT RATE kb/s	IF BW kHz	PREMOD kHz	TYPE	VIDEO kHz	BIT DET
X NRZ-L PCM/FM	1000	1500	700	CD	500	F/S
o NRZ-L PCM/FM	1000	1500	700	CD	750	F/S
* NRZ-L PCM/FM	1000	1500	700	CD	1000	F/S

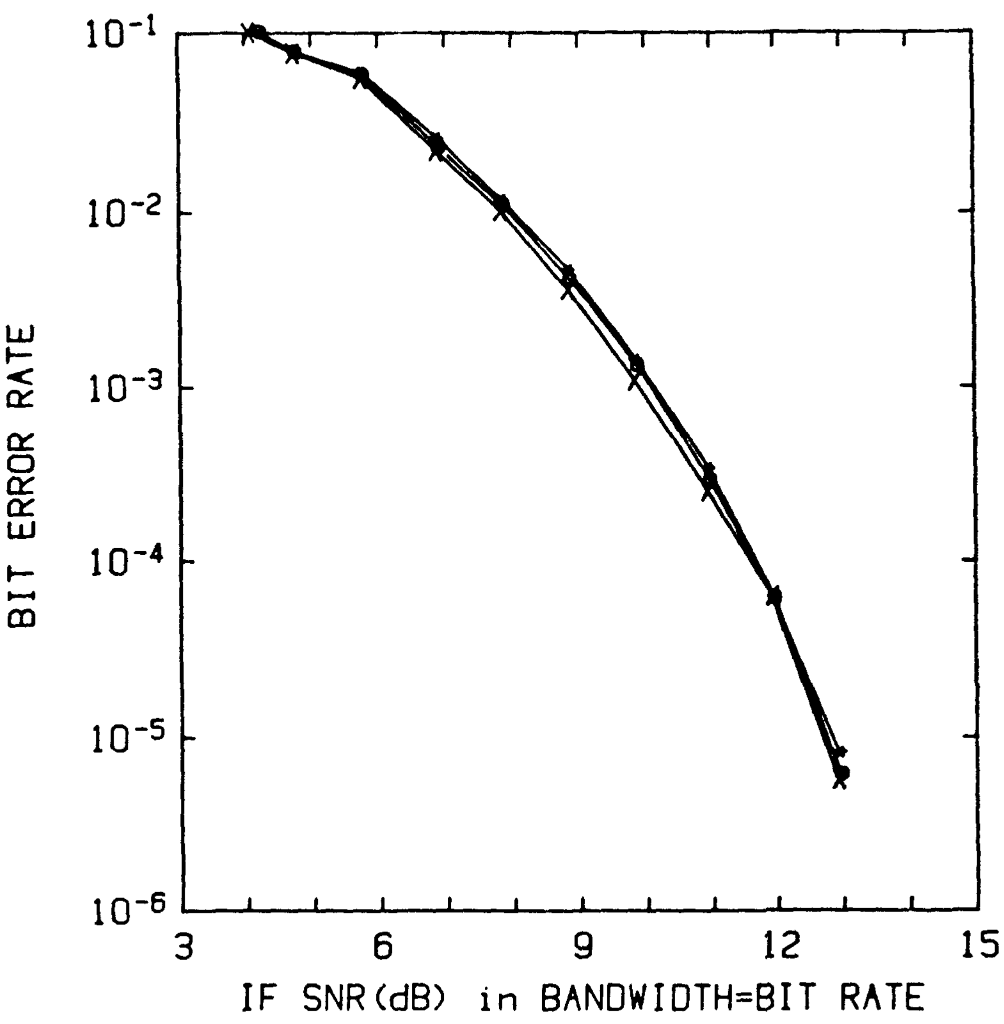

Figure 20. BER with Video BW=0.5, 0.75 and 1 Times Bit Rate.

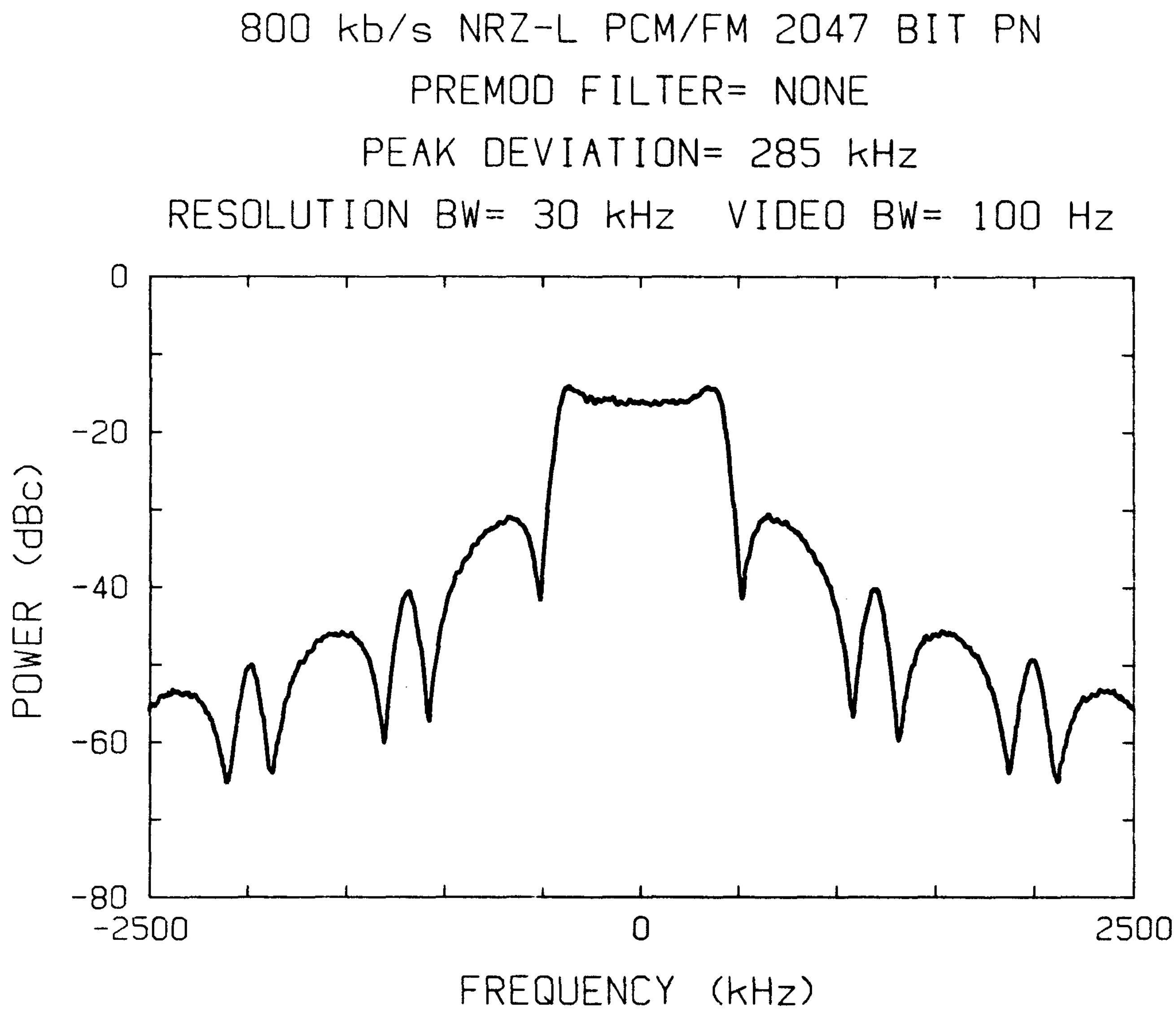

Figure 21. RF Spectrum PREMOD=None Peak DEV=0.35 Bit Rate.

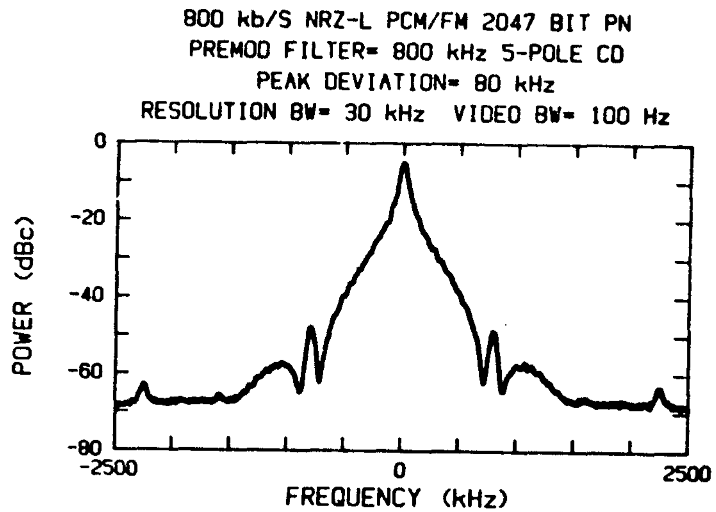

Figure 22. RF Spectrum PREMOD=800 kHz CD Peak DEV=0.1 Bit Rate

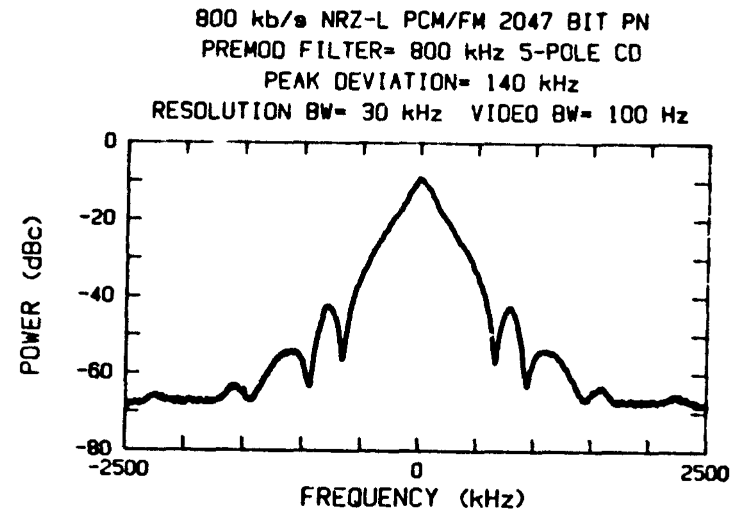

Figure 23. RF Spectrum PREMOD=800 kHz CD Peak DEV=0.175 Bit Rate

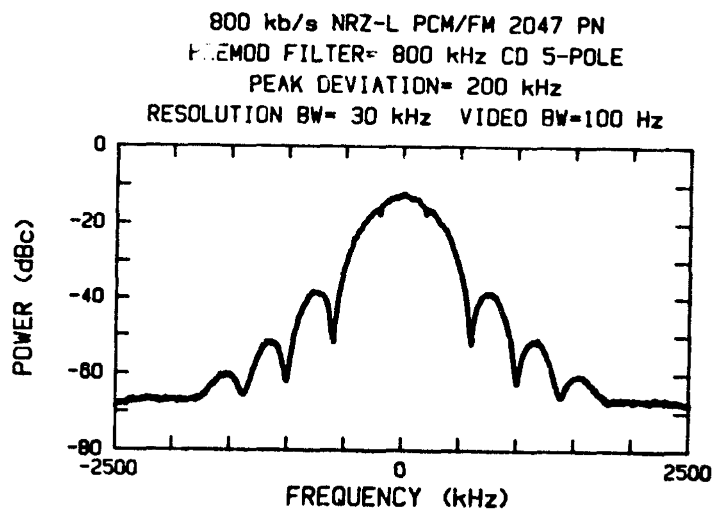

Figure 24. RF Spectrum PREMOD=800 kHz CD Peak DEV=0.25 Bit Rate

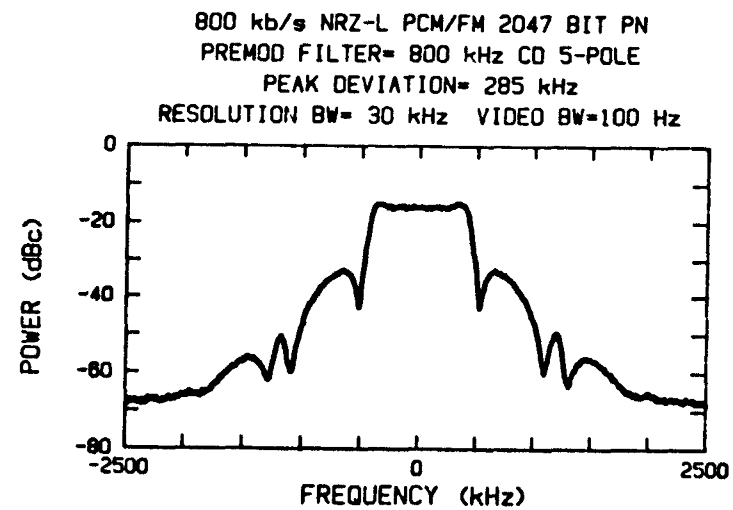

Figure 25. RF Spectrum PREMOD=800 kHz CD Peak DEV=0.35 Bit Rate

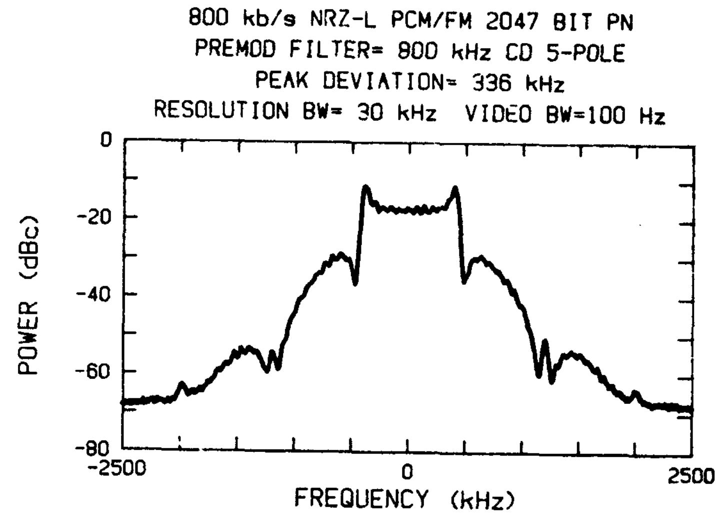

Figure 26. RF Spectrum PREMOD=800 kHz CD Peak DEV=0.42 Bit Rate

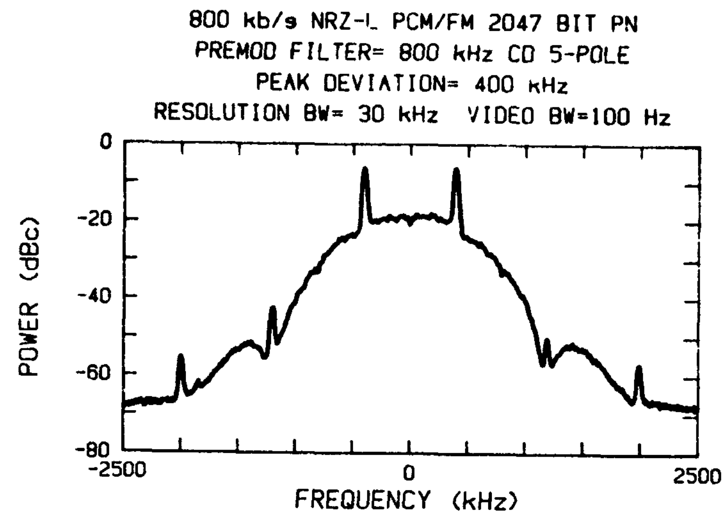

Figure 27. RF Spectrum PREMOD=800 kHz CD Peak DEV=0.50 Bit Rate

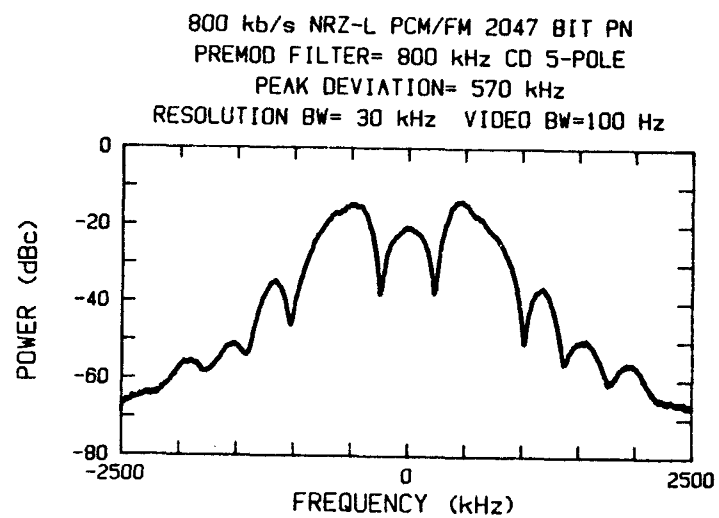

Figure 28. RF Spectrum PREMOD=800 kHz CD Peak DEV=0.71 Bit Rate

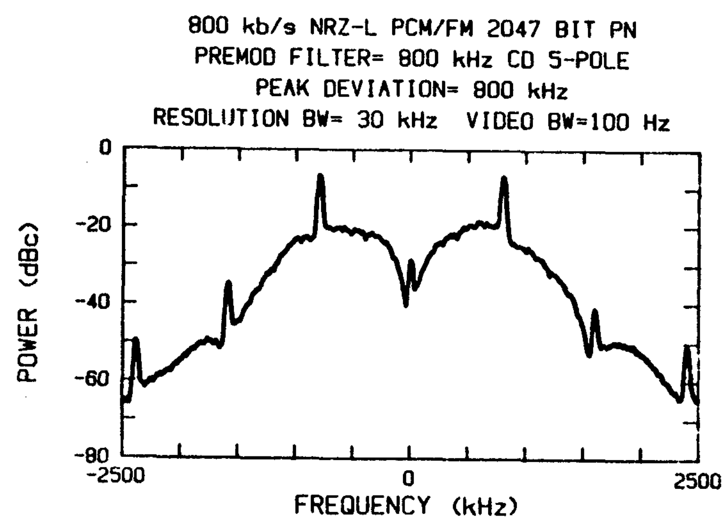

Figure 29. RF Spectrum PREMOD=800 kHz CD Peak DEV=1.00 Bit Rate

premodulation filter used was a 5-pole linear phase filter with the -3 dB roll-off point at 800 kHz for all eight spectra. The 99% power bandwidth versus peak deviation is shown in table 2 for four of the peak deviations listed above.

Table 2. RF Spectral Characteristics for Various Peak Deviations.

800 kb/s NRZ-L PCM/FM
800 kHz 5-pole Linear Phase Premodulation Filter

Peak Deviation		Occupied Bandwidth (kHz)	99% Power Bandwidth		% of Power in BW Equal to the Bit Rate
kHz	/Bit Rate		kHz	/Bit Rate	
200	0.25	1910	900	1.13	97.6
285	0.356	2040	1210	1.51	92.0
336	0.42	2170	1350	1.69	83.7
570	0.712	2960	1740	2.18	23.7

Table 3. RF Spectral Characteristics for Various Premodulation Filters.

800 kb/s NRZ-L PCM/FM
285 kHz Peak Deviation

Premodulation Filter		99% Power Bandwidth		Occupied Bandwidth (kHz)	% of Power in BW Equal to the Bit Rate
Bandwidth (kHz)	Type	kHz	/Bit Rate		
800	CD	1210	1.51	2040	92.0
800	CA	1330	1.66	2390	90.6
560	CD	930	1.16	2010	93.9
560	CA	950	1.19	2020	93.5
400	CD	890	1.11	1860	95.6
400	CA	890	1.11	1830	95.5
None		1420	1.78	4010	91.0
800	RC	1200	1.50	2500	92.6
560	RC	940	1.18	2500	93.7

The data presented in table 2 reveal that increasing the peak deviation from 0.356 times the bit rate to 0.42 times the bit rate increases the 99% power bandwidth by 11.6% and also increases the occupied bandwidth by 6.4%. The occupied bandwidth is defined as the bandwidth beyond which all components are 60 dB below the unmodulated carrier level when measured in a 3-kHz bandwidth. Doubling the peak deviation to 0.712 times the bit rate increases the 99% power bandwidth by 43.8% and increases the occupied bandwidth by 45.1%.

The effect on the RF spectrum as a result of using a variety of premodulation filter types is shown in figures 25, and 30 through 36. The 99% power bandwidths, the occupied bandwidths, and the percentage of the power in a bandwidth equal to the bit rate are shown in table 3.

The data in table 3 reveal that the 99% power bandwidth is usually not as wide when using a Bessel (constant delay) premodulation filter as compared to a Butterworth (constant amplitude) filter. The wider bandwidth is partially the result of the much larger overshoot of the Butterworth filter. The frequency deviation caused by the overshoot exceeds the nominal peak deviation (in this case 285 kHz) which is defined as the peak deviation without overshoot. The Bessel filter also attenuates signals below the -3 dB cutoff more than the Butterworth filter; however, outside the passband of the filter characteristic (above the -3 dB cutoff), the opposite is true. The 99% power bandwidth and the percentage of power in a bandwidth equal to the bit rate agree quite closely for the 5-pole Bessel and the 1-pole RC filters. It is noted however, that the occupied bandwidth is significantly narrower for the 5-pole Bessel filter than for the 1-pole RC filter. The reason for the differences in the response of the filters is that the 1-pole RC filter attenuation increases significantly more slowly than the attenuation of the Bessel filter at frequencies above the -3 dB point. The attenuation of the two filters is similar at frequencies below the -3 dB cutoff point.

All of the RF spectra presented in figures 21 through 36 were recorded with a spectrum analyzer resolution bandwidth of 30 kHz. The IRIG Standards specify a 3-kHz bandwidth for spectral occupancy measurements. Figure 37 is similar to figure 21 except the resolution bandwidth has been decreased to 3 kHz and the video bandwidth increased to 300 Hz. The sweep time in figure 37 was 15 seconds; while the sweep time in figure 21 was 5 seconds. In order to increase the statistical accuracy of figure 37 to the level of accuracy of figure 21 would require that the sweep time be 500 seconds. Therefore, the 30-kHz resolution bandwidth was chosen for the spectral displays in these descriptions. To convert the spectral amplitudes between the two filter bandwidths, it is necessary to subtract 10 dB ($10 \log_{10} 3/30$) from the 30-kHz value if the input is white noise. When the input contains discrete frequency components (delta functions in the frequency domain), the amplitude at the output of both filters would be the same; this assumes only one discrete component within the passband of the widest filter. Therefore, if discrete spectral components are not present, -50 dBc with a 30-kHz spectrum analyzer bandpass filter is essentially the same as -60 dBc with a 3-kHz bandpass filter. In reality, many discrete spectral components are present in this case, but the sum of many discrete spectral components looks like noise as far as the bandpass filter is concerned. In this case,

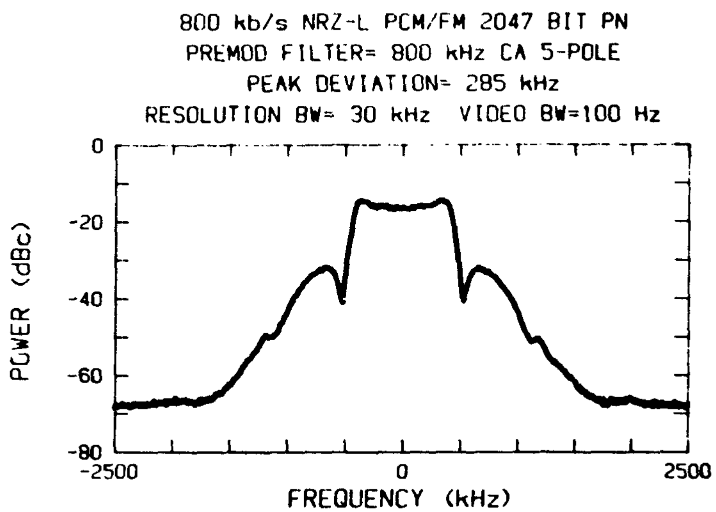

Figure 30. RF Spectrum PREMOD=800 kHz CA Peak DEV=0.35 Bit Rate

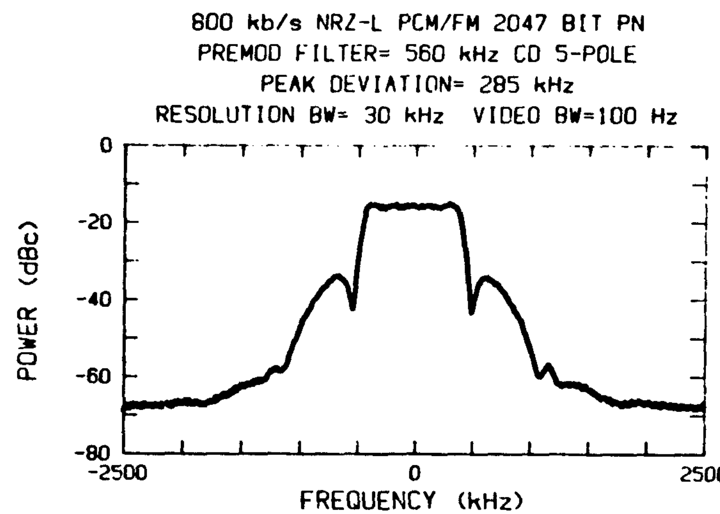

Figure 31. RF Spectrum PREMOD=560 kHz CD Peak DEV=0.35 Bit Rate

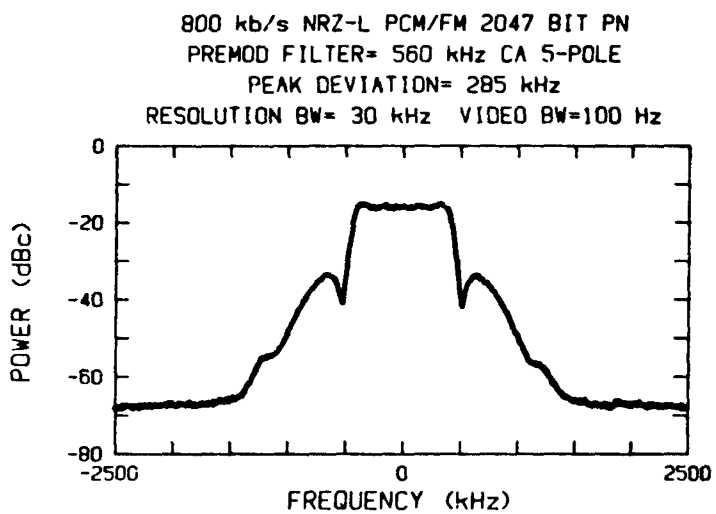

Figure 32. RF Spectrum PREMOD=560 kHz CA Peak DEV=0.35 Bit Rate

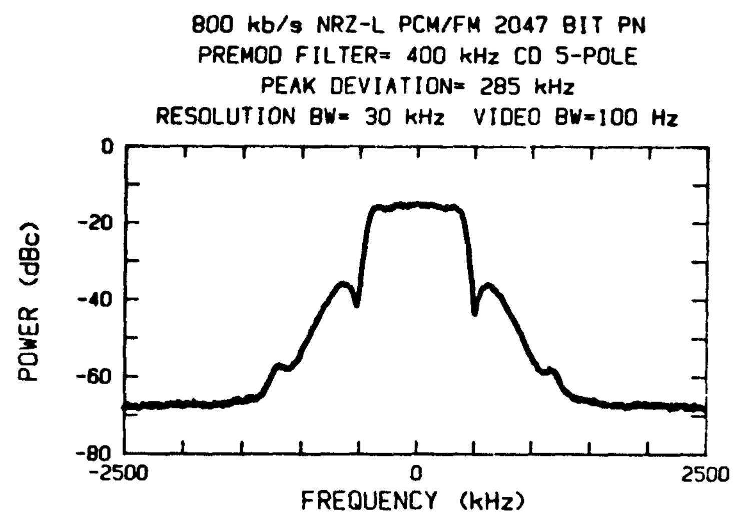

Figure 33. RF Spectrum PREMOD=400 kHz CD Peak DEV=0.35 Bit Rate

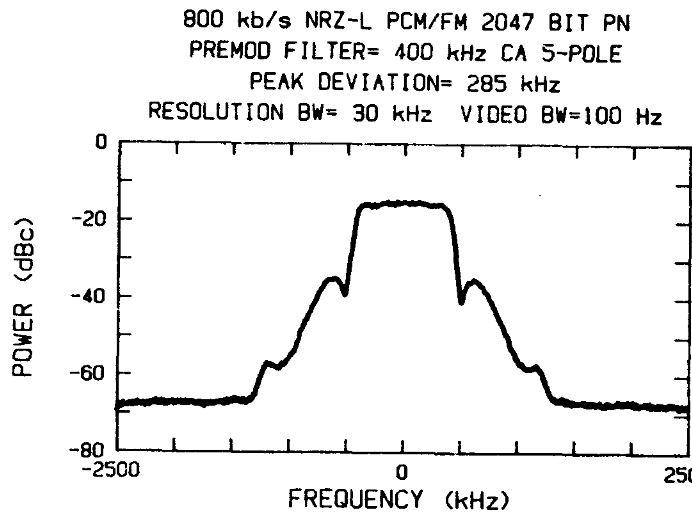

Figure 34. RF Spectrum PREMOD=400 kHz CA Peak DEV=0.35 Bit Rate

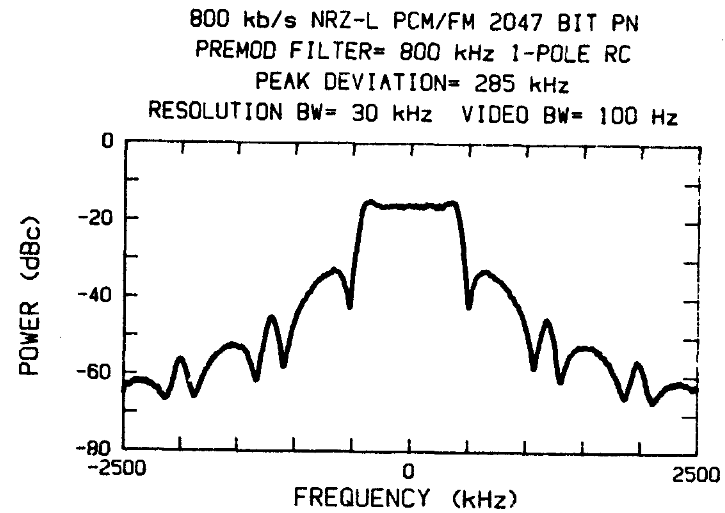

Figure 35. RF Spectrum PREMOD=800 kHz RC Peak DEV=0.35 Bit Rate

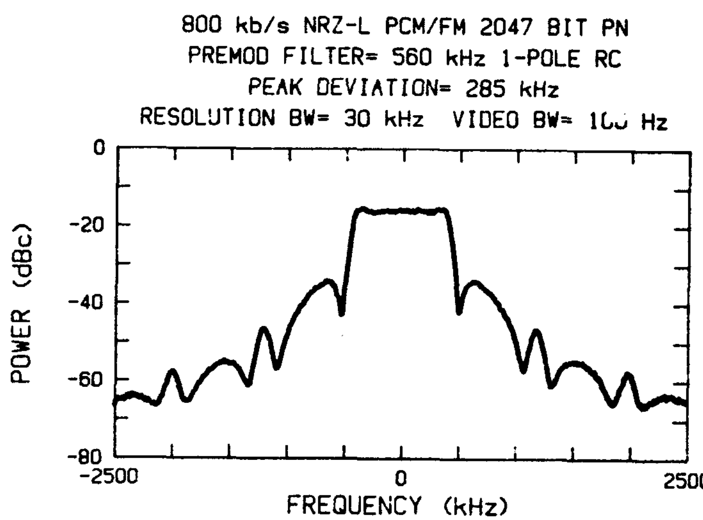

Figure 36. RF Spectrum PREMOD=560 kHz RC Peak DEV=0.35 Bit Rate

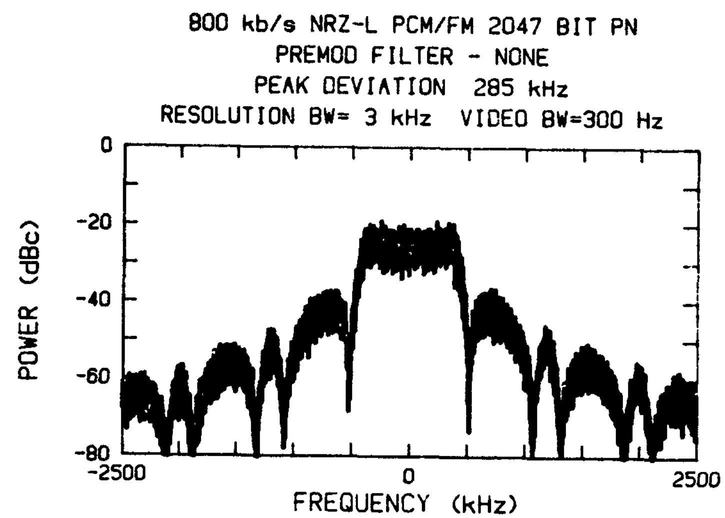

Figure 37. RF Spectrum PREMOD=None Peak DEV=0.35 Bit Rate (3 kHz)

it is not possible to extend the extrapolation to a 100-Hz bandpass filter because the spectral components are spaced every 800,000/2047 Hz or approximately 391 Hz apart. Therefore, a 100-Hz bandpass filter would resolve the individual components.

Figures 38 and 39 show the spectra that result when the bit stream contains a repeating 16-bit word. The 16-bit word for figure 38 was "1111000100110100," which is a 15-bit pseudo-noise sequence with a zero added at the end for symmetry. The 16-bit word for figure 39 was "101000100010000," which is the word from figure 38 with every other "1" converted to a "0." The spectrum in figure 39 is obviously not symmetrical. The spectrum in figure 38 is somewhat symmetrical, but there are significant differences between the upper and lower halves of the spectrum. In general, FM spectra are not symmetrical unless the input to the FM modulator is symmetrical. For example, a single sine wave modulating an FM generator produces a symmetrical RF spectrum.

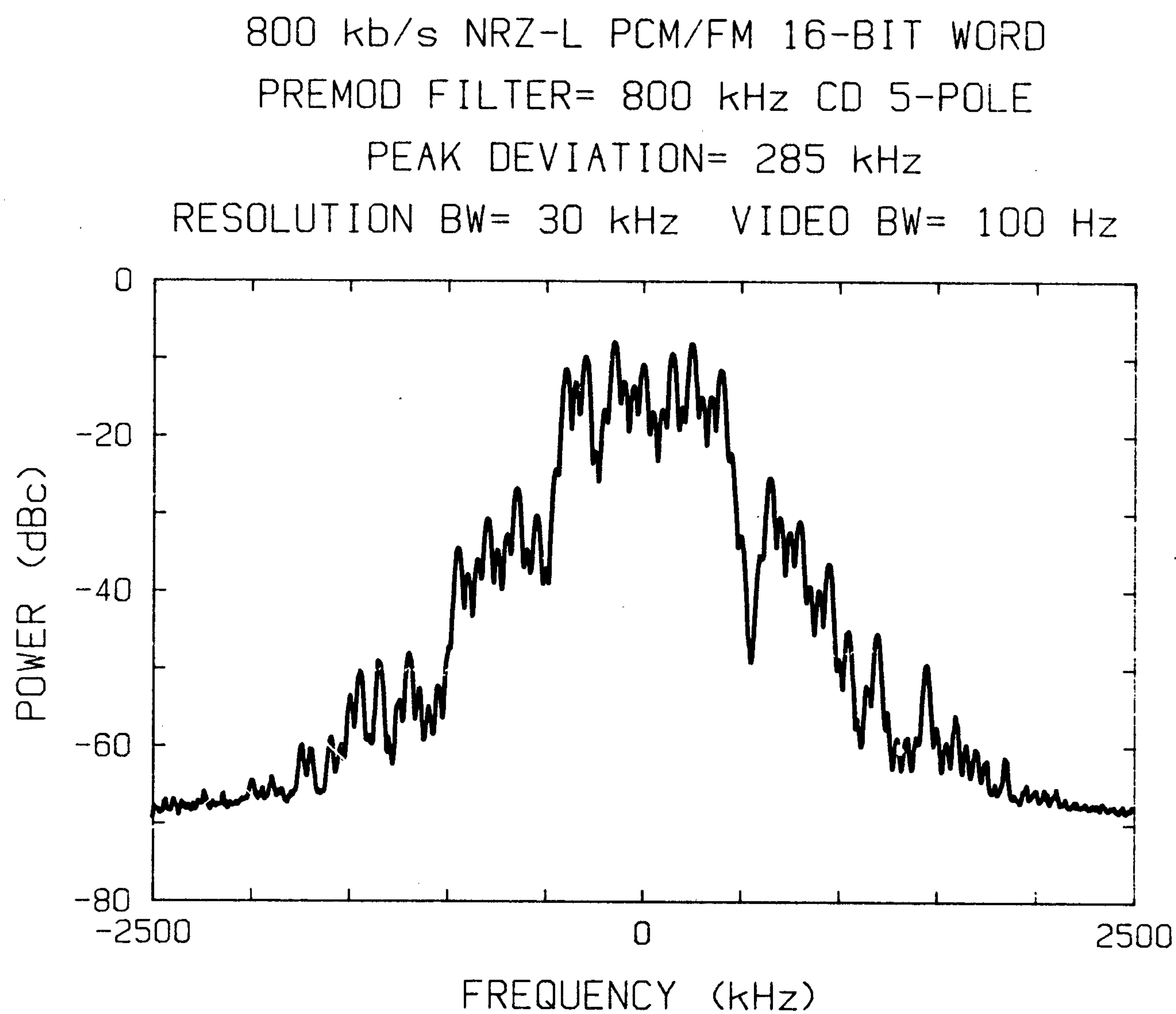

Figure 38. RF Spectrum 16-Bit Word.

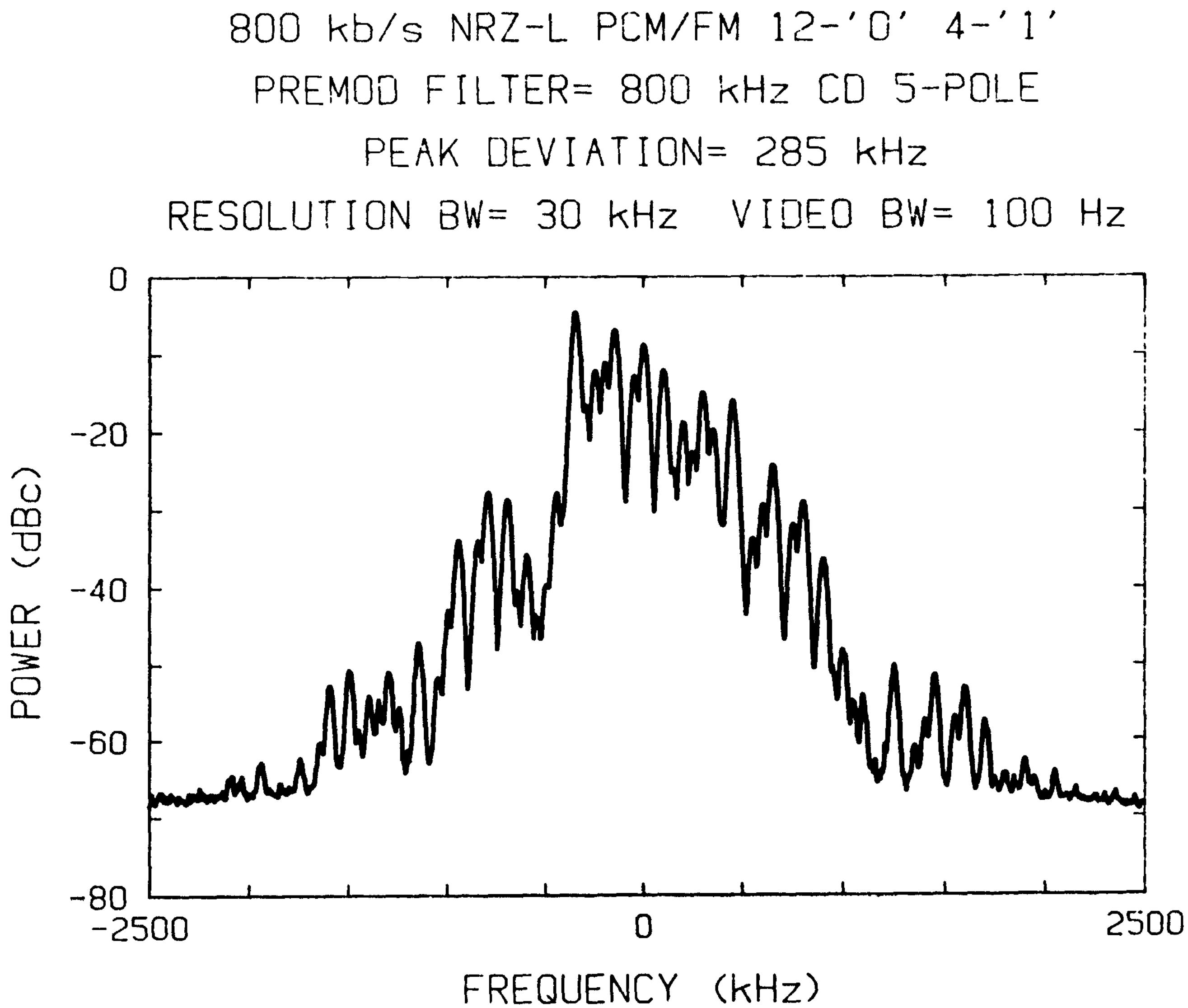

Figure 39. RF Spectrum 16-Bit Word (3/4 Zeros).

BIPHASE PCM/FM

Introduction

Biphase pulse code modulation/frequency modulation (Biphase PCM/FM) is a method used to send digital data over a transmission link. The most commonly used code for biphase PCM/FM is the biphase level (BIO-L) code. This code represents a ONE by a high level for the first half of the bit time and a low level for the second half of the bit time. A ZERO is the exact opposite of a ONE. The advantages of biphase PCM/FM over NRZ PCM/FM include:

1. Biphase has no DC component; therefore, AC-coupled transmitters can be used.

2. Biphase has a transition every bit period. This makes bit synchronization easier.

The disadvantages of biphase PCM/FM compared to NRZ PCM/FM include:

1. Biphase PCM/FM requires approximately twice the bandwidth of NRZ PCM/FM.

2. Biphase PCM/FM requires approximately 3 dB more IF SNR in a bandwidth equal to the bit rate for the same BER, compared to NRZ PCM/FM.

Selection of Peak Deviation

The optimum peak deviation for biphase PCM/FM is approximately 0.65 times the bit rate; i.e., a 1.0-Mb/s bit stream should have a peak deviation of 650 kHz and a peak-to-peak deviation of 1,300 kHz.[7] This optimum value of peak deviation is valid when using IF bandwidths that are between 1.8 and 4 times the bit rate and for systems where the incidental FM is much less than the peak deviation. If the predetection bandwidth is wider than four times the bit rate, the optimum peak deviation is greater than 0.65 times the bit rate (see figure 40). If the predetection bandwidth is much wider than the bit rate, biphase PCM/PM will usually be a better choice than biphase PCM/FM because of its better BER versus IF SNR performance.

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[7] Tan, C. H., T. T. Tjhung, and H. Singh. "Performance of Narrow-Band Manchester Coded FSK With Discriminator Detection," in IEEE Transactions on Communications, Vol. COM-31, pp. 659-667, May 1983.

MODULATION TYPE	BIT RATE kb/s	IF BW kHz	PREMOD kHz	TYPE	PEAK DEV	BIT DET
+ BIO-L PCM/FM	500	3000	1000	CD	325	
o BIO-L PCM/FM	500	3000	1000	CD	950	
* BIO-L PCM/FM	500	1000	1000	CD	325	

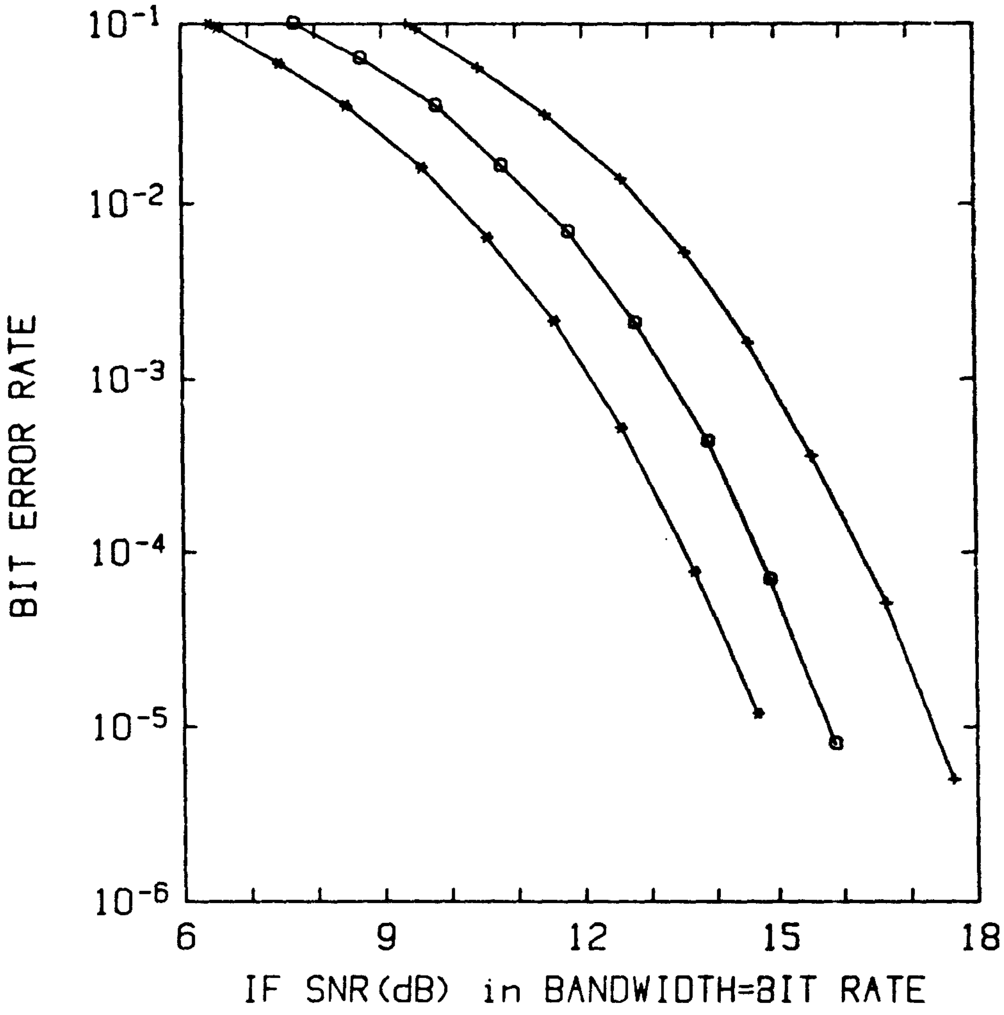

Figure 40. BER for IF BW=2 and 6 Times Bit Rate.

The BER versus IF SNR performance of biphase PCM/FM is shown in figures 41 and 42 for peak deviations equal to 0.50, 0.65, and 0.80 times the bit rate and IF bandwidths of two and three times the bit rate. The IF SNR in a bandwidth equal to the bit rate for a 10^{-4} BER was 13.5 dB for an IF bandwidth equal to twice the bit rate and 14.4 dB for an IF bandwidth equal to three times the bit rate with a peak deviation equal to 0.65 times the bit rate.

Selection of Premodulation Filter

The best premodulation filter is the widest filter that allows the RF spectral occupancy requirements to be met. A low pass filter with a -3 dB bandwidth equal to or greater than 1.4 times the bit rate will not cause a significant increase in the BER (see figure 43). The use of a premodulation filter bandwidth equal to the bit rate degrades the data quality by at least 1 dB for BERs of 10^{-4} (and lower). The BER versus IF SNR performance is essentially the same with linear phase and constant amplitude premodulation filters.

Selection of Receiver IF Bandwidth

The optimum receiver IF bandwidth is equal to approximately two times the bit rate for biphase level PCM/FM. Reference 7 lists an optimum IF bandwidth of 1.8 times the bit rate. The variation of BER with the ratio of IF bandwidth to bit rate is illustrated in figure 44. The IF bandwidth was fixed at 1,000 kHz (actually measured to be approximately 1,100 kHz) and the bit rate, premodulation filter bandwidth, and peak deviation were varied. The premodulation filter bandwidth was set to twice the bit rate and the peak deviation was set to 0.65 times the bit rate. For BERs between 10^{-4} and 10^{-5}, the performance at 500 and 600 kb/s was essentially the same and better than the performance at 400 and 700 kb/s. The ratio of measured IF bandwidth to bit rate was approximately 2.2 and 1.8 for 500 and 600 kb/s, respectively. This supports the optimum IF bandwidth setting of approximately twice the bit rate. Figure 45 shows the BER versus IF SNR performance for bandwidths equal to 2, 3, and 6 times the bit rate. The use of excessively wide IF filters with predetection recording should be avoided. The IF filter should not be wider than two times the predetection carrier frequency. Also, the biphase bit rate should not exceed one-half of the predetection carrier frequency.

Selection of Demodulator Video Bandwidth

The demodulator video bandwidth should not be set to a value less than the bit rate. There is very little difference in BER performance between video filters with bandwidths between one and three times the bit rate.

Selection of PCM Bit Synchronizer Bit Detector

Most PCM bit synchronizers do not offer a choice of bit detector type for biphase signals.

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[7] Ibid.

MODULATION TYPE	BIT RATE kb/s	IF BW kHz	PREMOD kHz TYPE	PEAK DEV	BIT DET
+ BIO-L PCM/FM	500	1000	1000 CD	250	
o BIO-L PCM/FM	500	1000	1000 CD	400	
* BIO-L PCM/FM	500	1000	1000 CD	325	

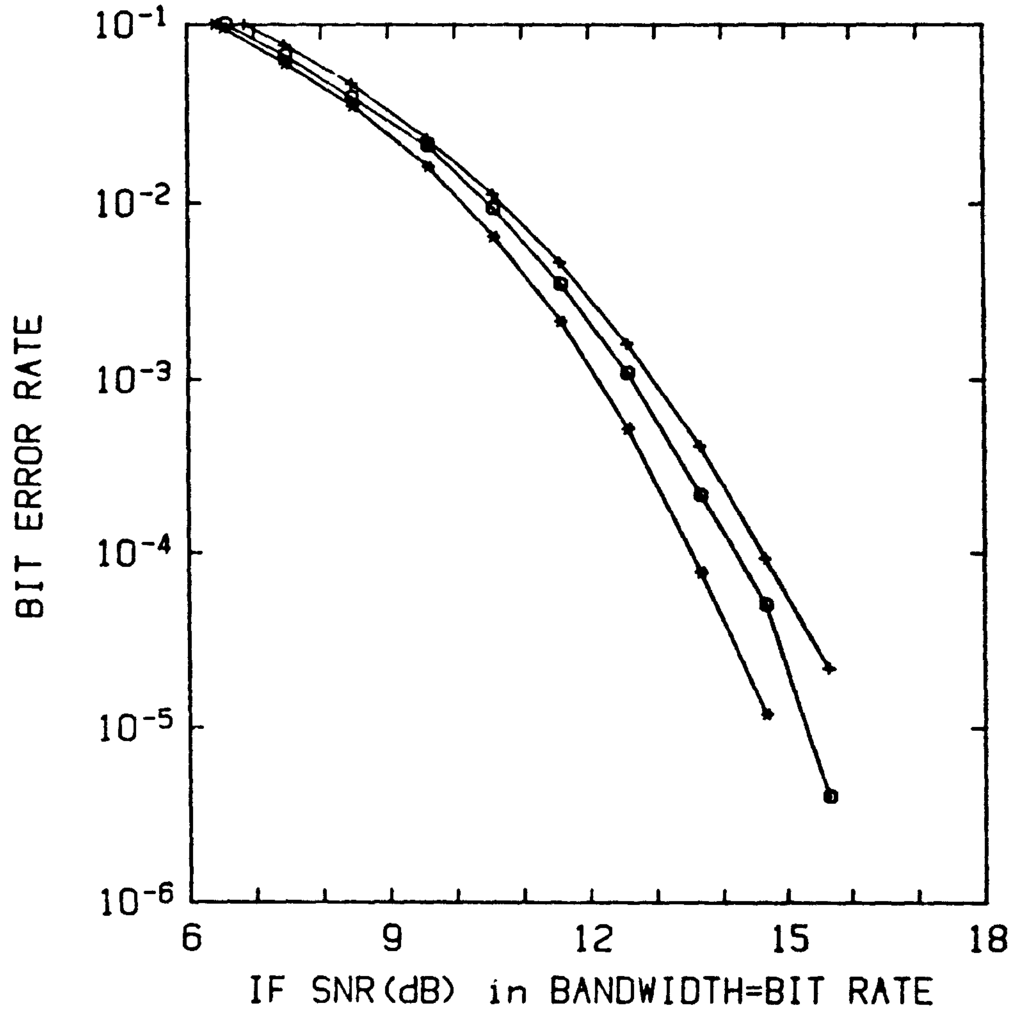


Figure 41. BER for Peak DEV=0.5, 0.65 and 0.8 Bit Rate.

MODULATION TYPE	BIT RATE kb/s	IF BW kHz	PREMOD kHz	PREMOD TYPE	PEAK DEV	BIT DET
+ BIO-L PCM/FM	500	1500	700	CD	250	
o BIO-L PCM/FM	500	1500	700	CD	400	
* BIO-L PCM/FM	500	1500	700	CD	325	

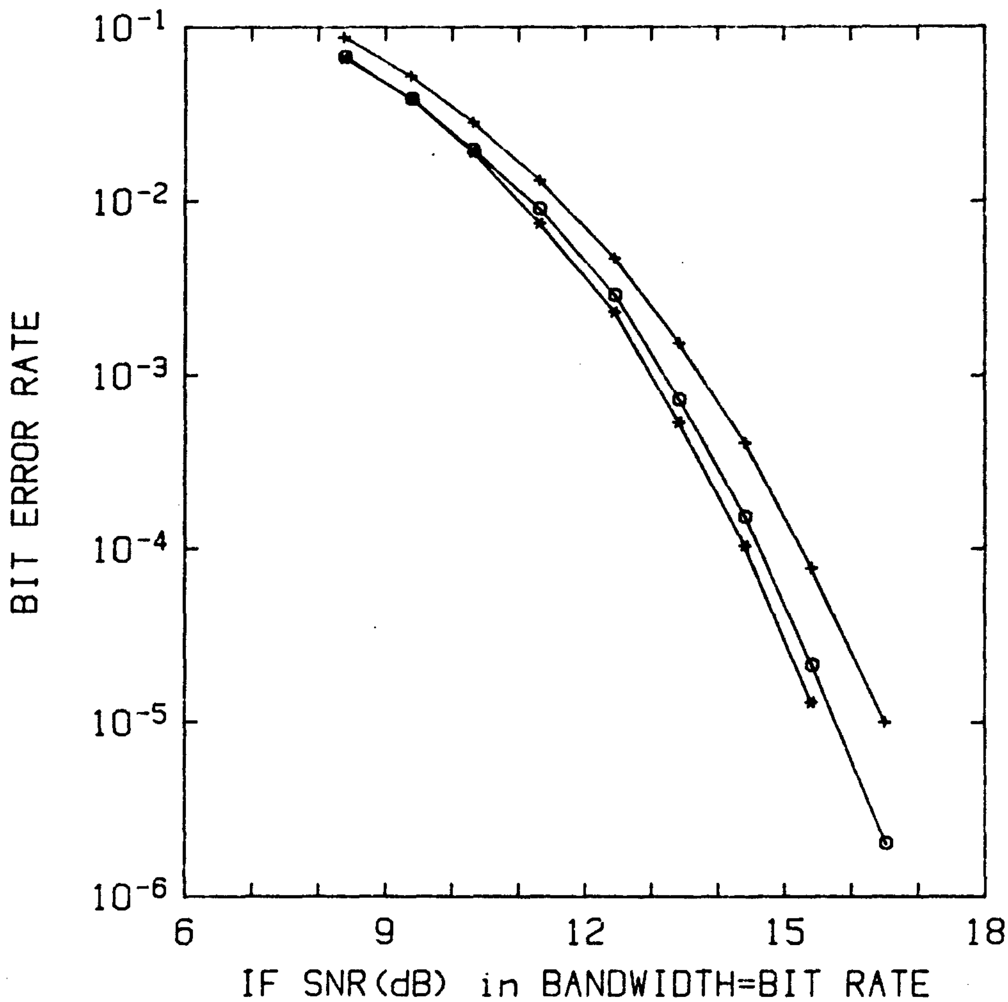


Figure 42. BER for Peak DEV=0.5, 0.65 and 0.8 Bit Rate.

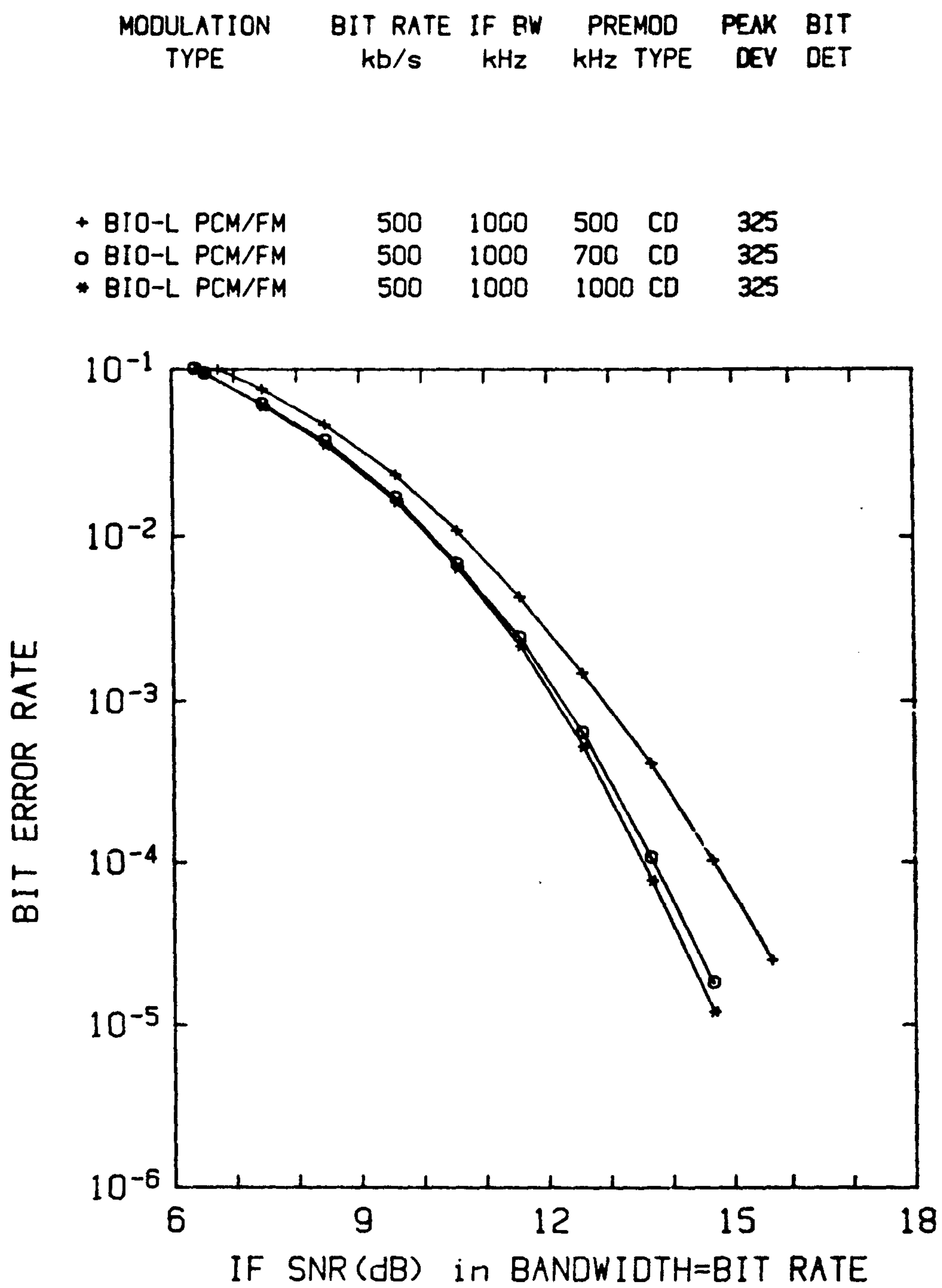


Figure 43. BER for PREMOD BW=1, 1.4 and 2 Bit Rate.

MODULATION TYPE	BIT RATE kb/s	IF BW kHz	PREMOD kHz	TYPE	PEAK DEV	BIT DET
o BIO-L PCM/FM	700	1000	1400	CD	455	
+ BIO-L PCM/FM	600	1000	1200	CD	390	
* BIO-L PCM/FM	500	1000	1000	CD	325	
0 BIO-L PCM/FM	400	1000	800	CD	260	

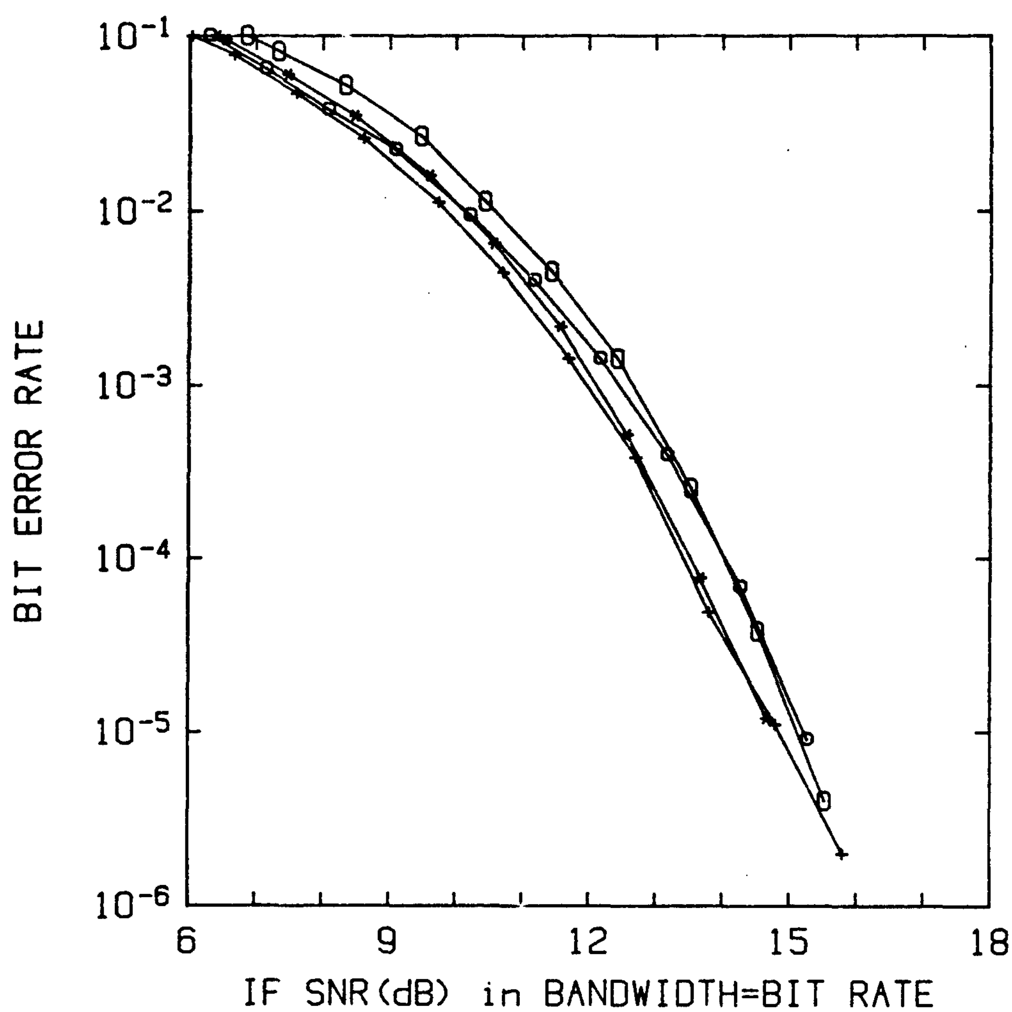


Figure 44. BER for IF BW/Bit Rate=1.4, 1.67, 2 and 2.5.

MODULATION TYPE	BIT RATE kb/s	IF BW kHz	PREMOD kHz	PREMOD TYPE	PEAK DEV	BIT DET
+ BIO-L PCM/FM	500	3000	1000	CD	325	
o BIO-L PCM/FM	500	1500	1000	CD	325	
* BIO-L PCM/FM	500	1000	1000	CD	325	

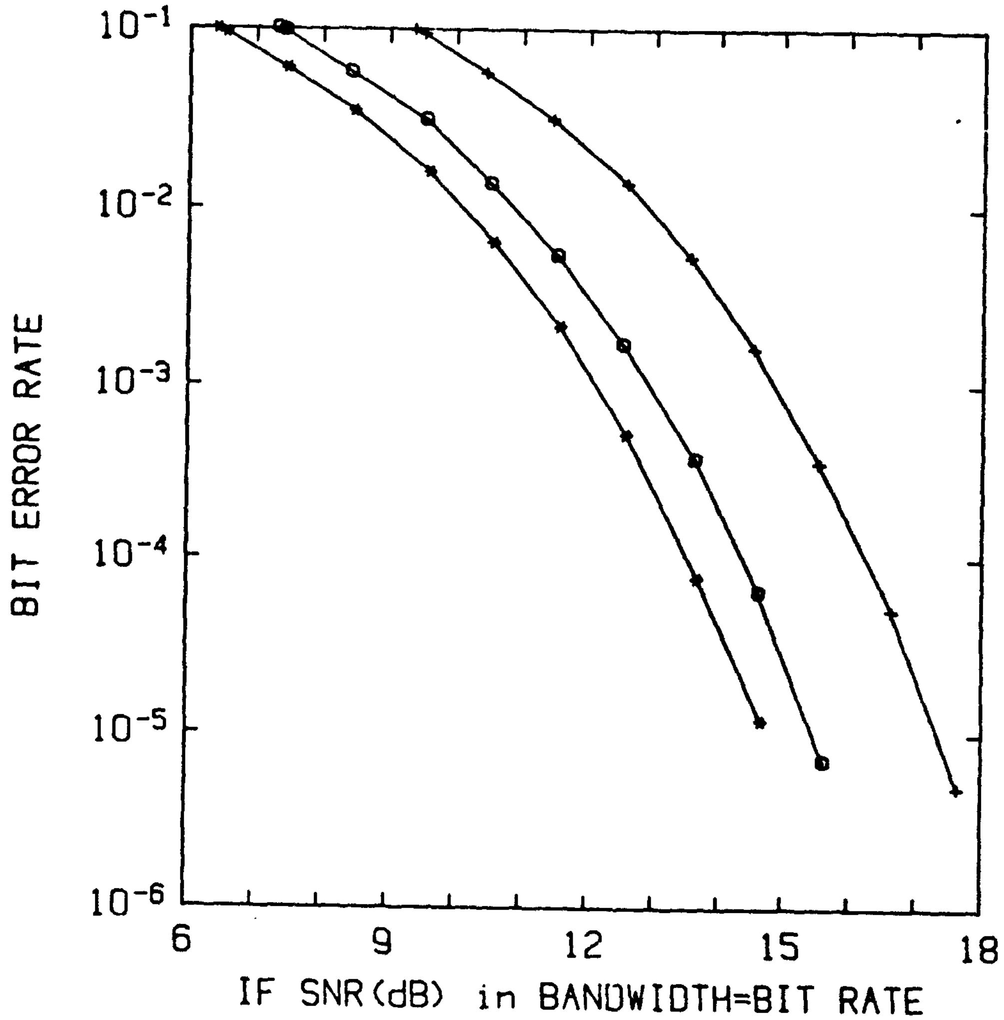


Figure 45. BER for IF BW/Bit Rate=2, 3 and 6.

RF Spectra

Sample biphase level PCM/FM RF spectra are shown in figures 46 through 51. These spectra have spikes at the center frequency and also at multiples of the bit rate on both sides of the center frequency. The occupied bandwidth is listed in table 4 for these conditions. The occupied bandwidth is six times the bit rate for premodulation filter bandwidths equal to the bit rate and also for a constant amplitude premodulation filter with a bandwidth equal to twice the bit rate for the optimum peak deviation. The occupied bandwidth is equal to eight times the bit rate with a constant delay premodulation filter bandwidth equal to twice the bit rate and the optimum peak deviation. The filters used for these spectral plots were 5-pole low pass filters.

Table 4. Occupied Bandwidth of 400 kb/s Biphase Level PCM/FM for Various Premodulation Filters and Peak Deviations.

Premodulation Filter		Peak Deviation	Occupied Bandwidth	
Bandwidth (kHz)	Type	(kHz)	kHz	/Bit Rate
800	CD	260	3200	8
800	CD	200	3200	8
800	CD	320	4000	10
800	CA	260	2400	6
400	CD	260	2400	6
400	CA	260	2400	6

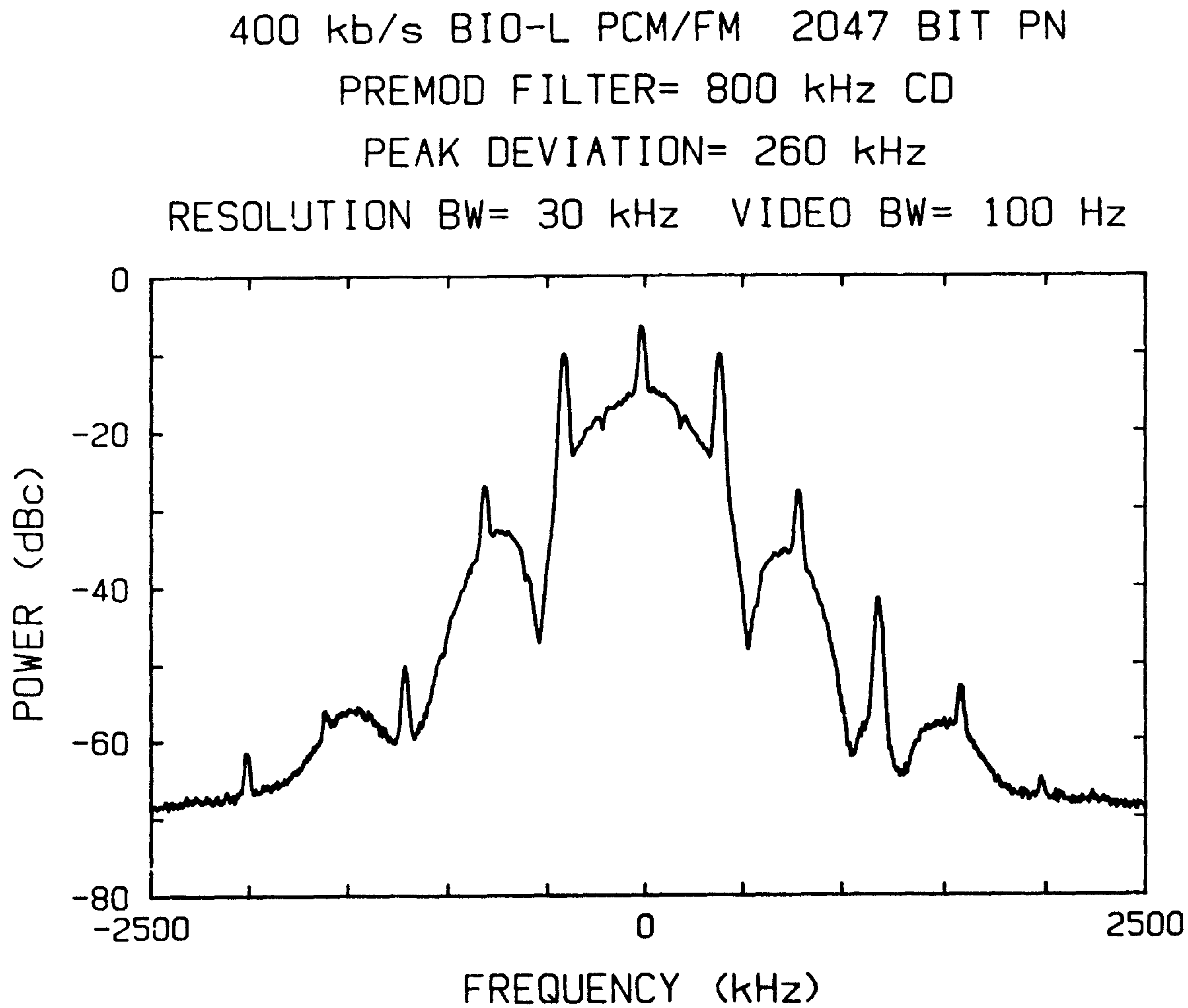


Figure 46. RF Spectrum PREMOD=800 kHz CD Peak DEV=0.65 Bit Rate.

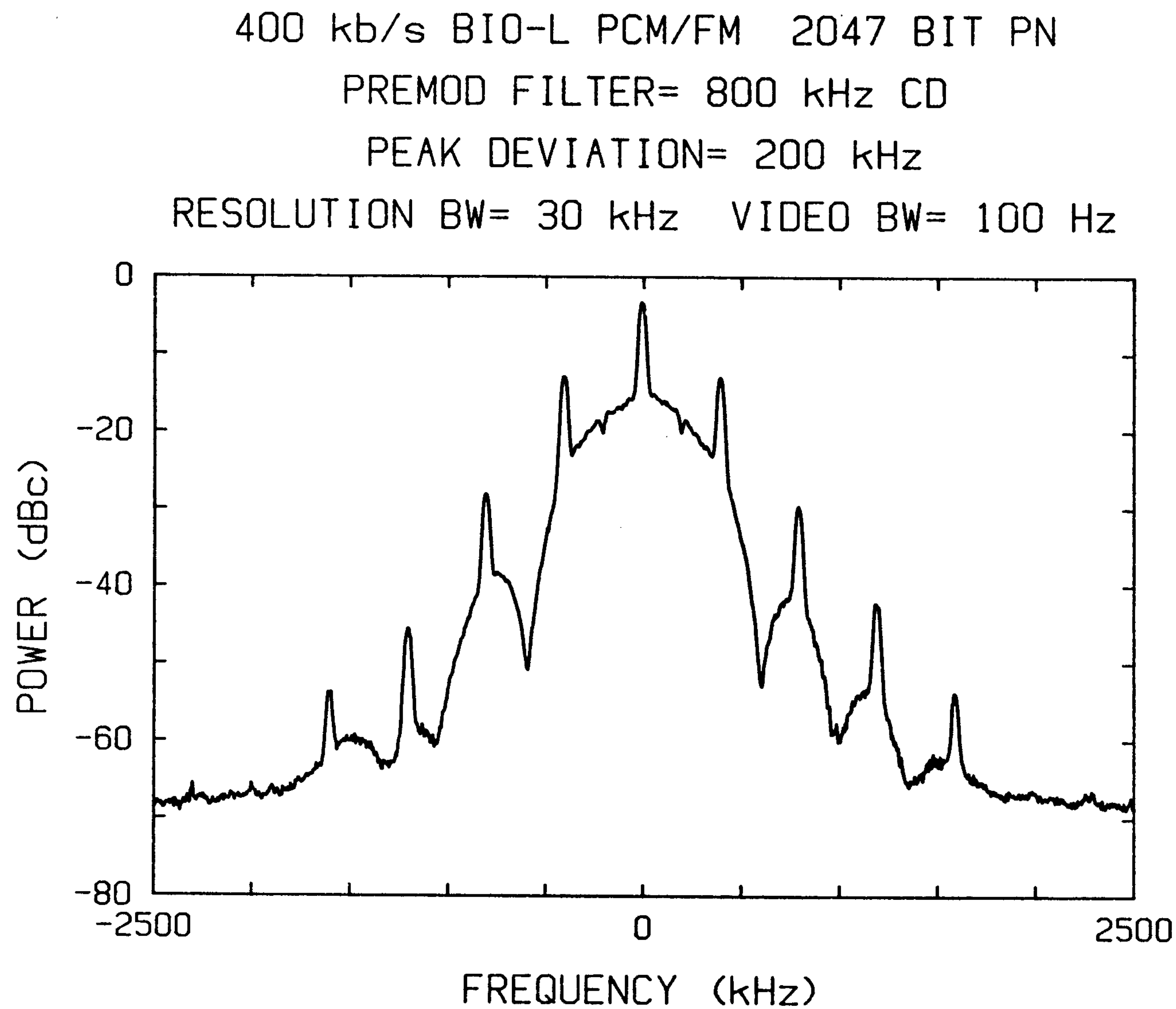


Figure 47. RF Spectrum PREMOD=800 kHz CD Peak DEV=0.50 Bit Rate.

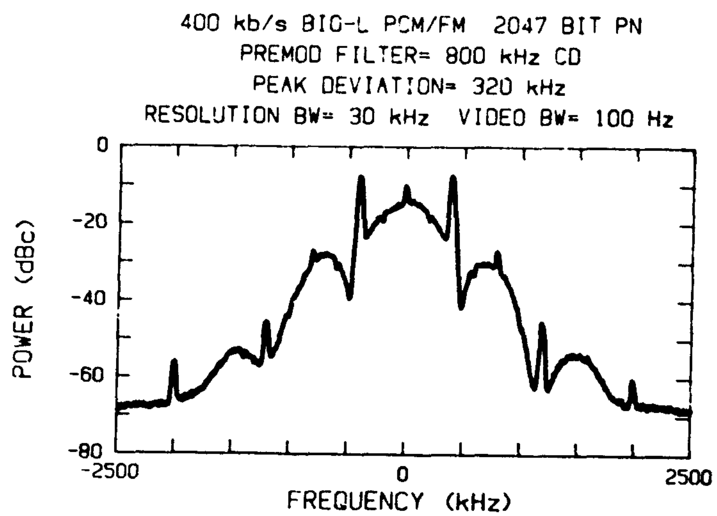


Figure 48. RF Spectrum PREMOD=800 kHz CD Peak DEV=0.80 Bit Rate.

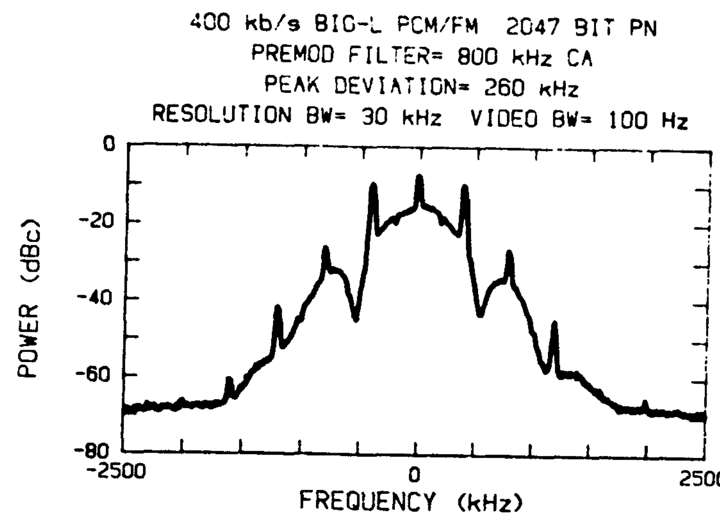


Figure 49. RF Spectrum PREMOD=800 kHz CA Peak DEV=0.65 Bit Rate.

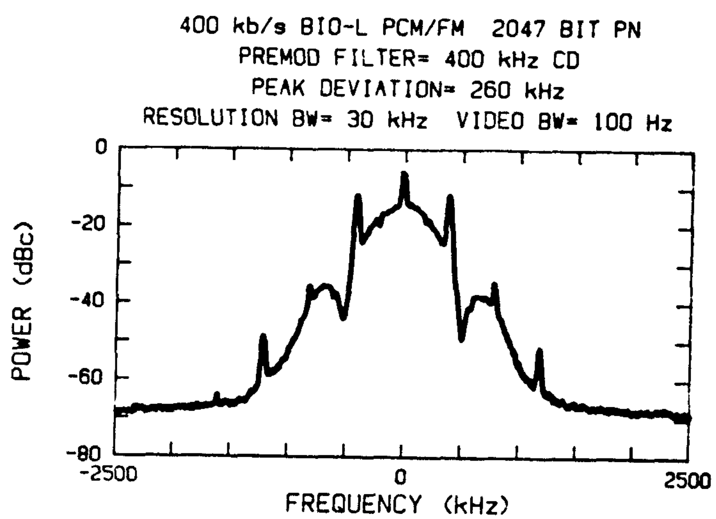


Figure 50. RF Spectrum PREMOD=400 kHz CD Peak DEV=0.65 Bit Rate.

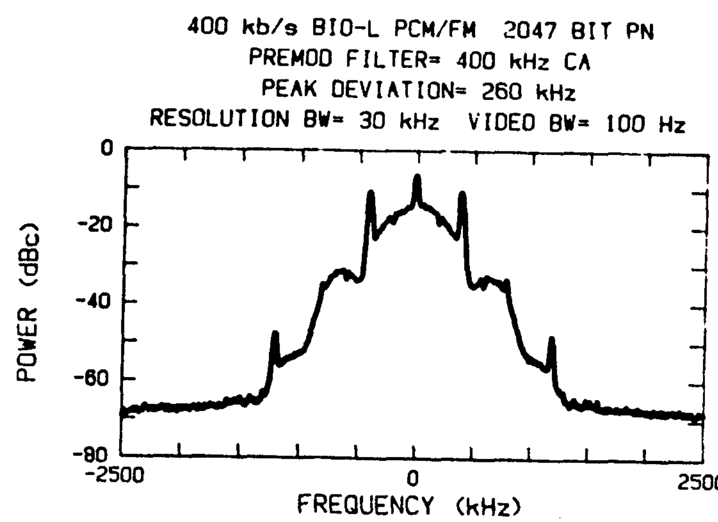


Figure 51. RF Spectrum PREMOD=400 kHz CA Peak DEV=0.65 Bit Rate.

NRZ PCM/PM

Introduction

Pulse code modulation/phase modulation with 90-degree peak deviation (PCM/PM ($\pm 90^{\circ}$)) is a method of sending digital data over a transmission link where the carrier phase is shifted +90 degrees to represent one state of a binary signal, and shifted -90 degrees to represent the other state of the binary signal. The most commonly used codes for NRZ PCM/PM ($\pm 90^{\circ}$) are the mark (M) and space (S) codes. The mark and space codes are used because the demodulated output signal can be either inverted or not inverted with equal probability. Since the NRZ-M and NRZ-S codes are polarity insensitive, the unknown polarity does not matter.

Bit errors in NRZ PCM/PM ($\pm 90^{\circ}$) are caused by the effects of additive, white, gaussian noise plus intersymbol interference, timing errors, etc. This makes it relatively simple to derive an expression for the bit error rate as follows:

$$BER = 1/2 \; \text{erfc} \left(\sqrt{E_B/N_O} \; \text{Cos} \; \phi \right)$$

Where:

E_B is the signal energy per bit
N_O is the noise power spectral density
ϕ is the carrier recovery loop tracking error
erfc is the complementary error function

Note that the expression assumes unfiltered NRZ-L data and ideal bit detection. The BER for NRZ-M and NRZ-S is approximately twice the BER listed above; actually 2BER(1-BER).

Selection of Peak Deviation

The peak carrier deviation that produces the minimum bit error rate is a function of the premodulation filter, the demodulator type and loop bandwidth, and the bit pattern. The bit error rate is relatively insensitive to small changes in the peak deviation. A change in peak deviation from ± 90 degrees to ± 100 degrees (or ± 80 degrees) with no premodulation filtering requires a 0.13 dB (theoretical value) higher SNR to produce the same BER. Figures 52 through 56 present BER data versus IF SNR for three different premodulation filter bandwidths and peak deviations of 80, 90, and 100 degrees. Two different PSK demodulators were used. Model A for figures 52 and 56 and Model B for figures 53, 54, and 55. There is no

MODULATION TYPE	BIT RATE kb/s	IF BW kHz	PREMOD kHz TYPE	PEAK DEV	BIT DET
× NRZ-M PCM/PM	500	3000	1000 CD	80	I/D
+ NRZ-M PCM/PM	500	3000	1000 CD	100	I/D
o NRZ-M PCM/PM	500	3000	1000 CD	90	I/D
* NRZ-M PSK THEORY					

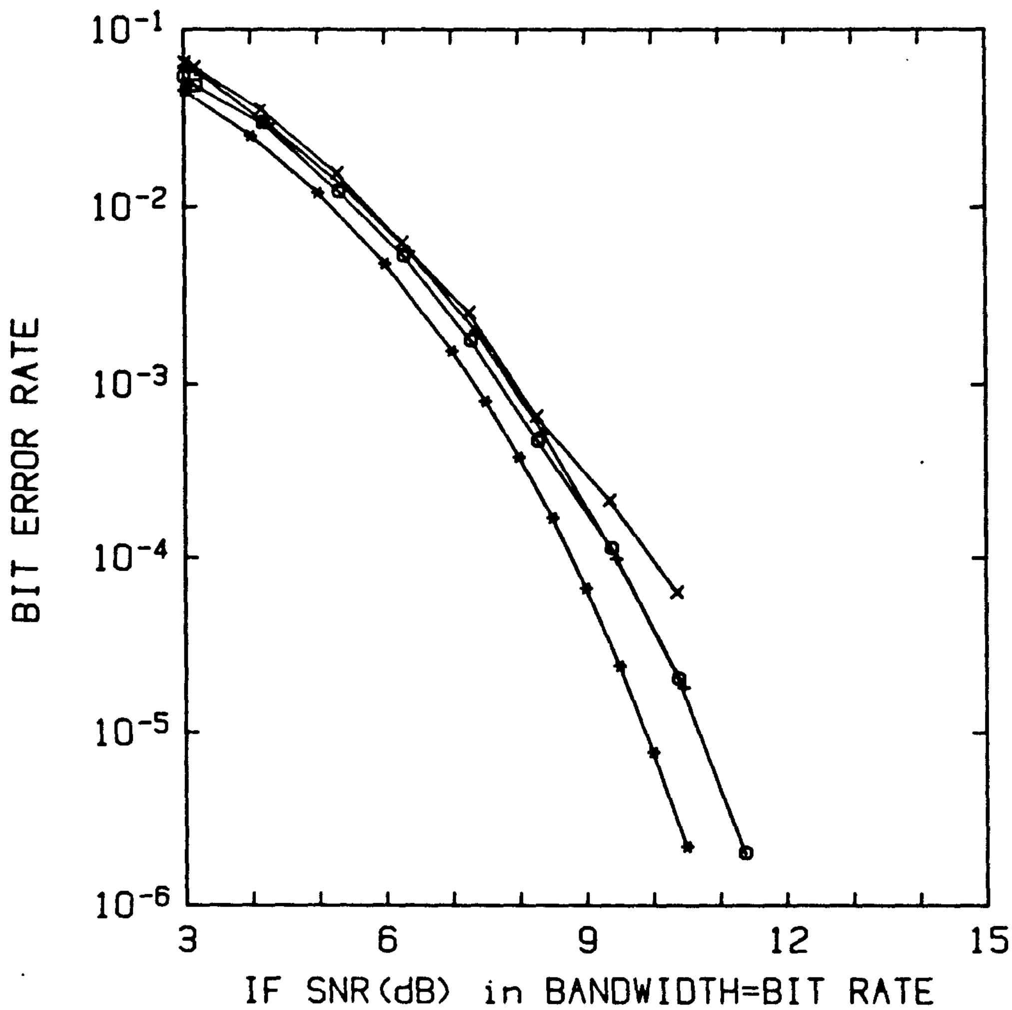


Figure 52. BER for 80, 90 and 100 Degrees Peak DEV (NRZ-M).

MODULATION TYPE	BIT RATE kb/s	IF BW kHz	PREMOD kHz TYPE	PEAK DEV	BIT DET
x NRZ-M PCM/PM	500	3000	1000 CD	80	I/D
+ NRZ-M PCM/PM	500	3000	1000 CD	100	I/D
o NRZ-M PCM/PM	500	3000	1000 CD	90	I/D
* NRZ-M PSK THEORY					

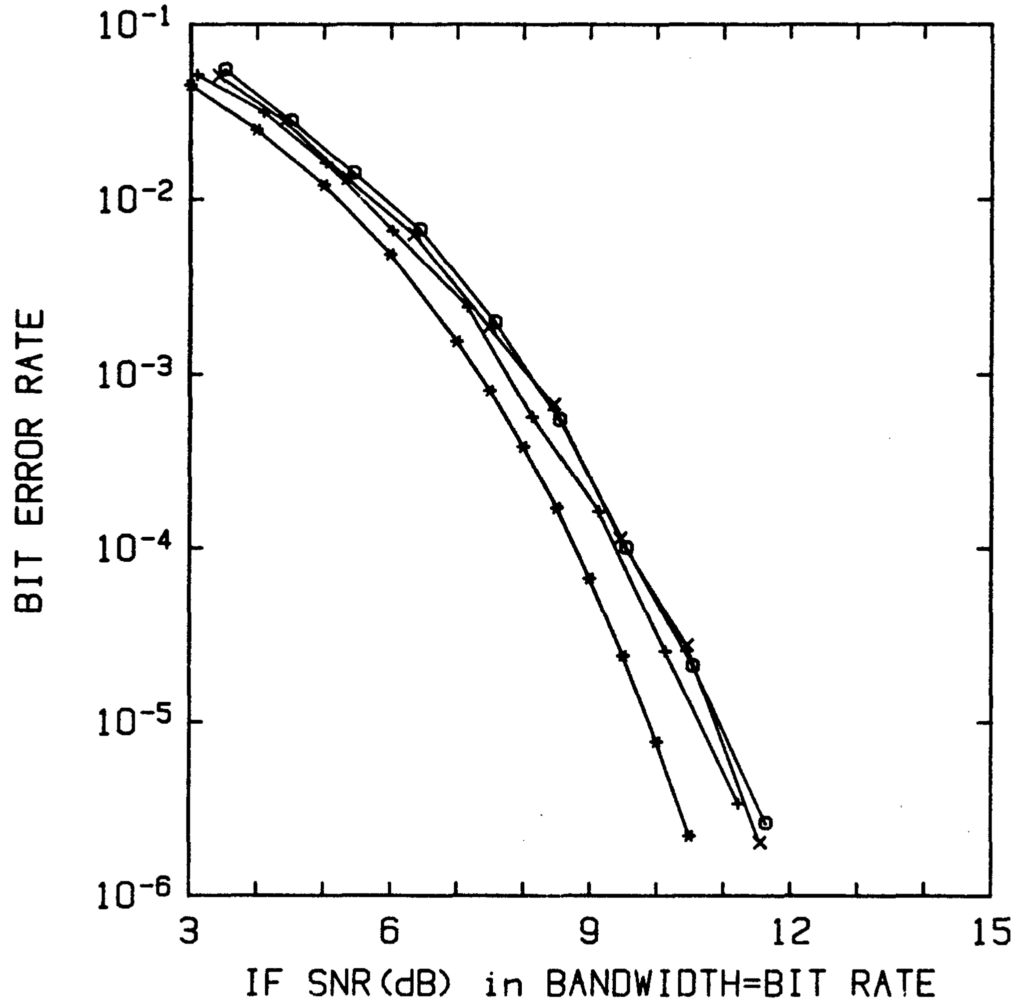


Figure 53. BER for 80, 90 and 100 Degrees Peak DEV (NRZ-M).

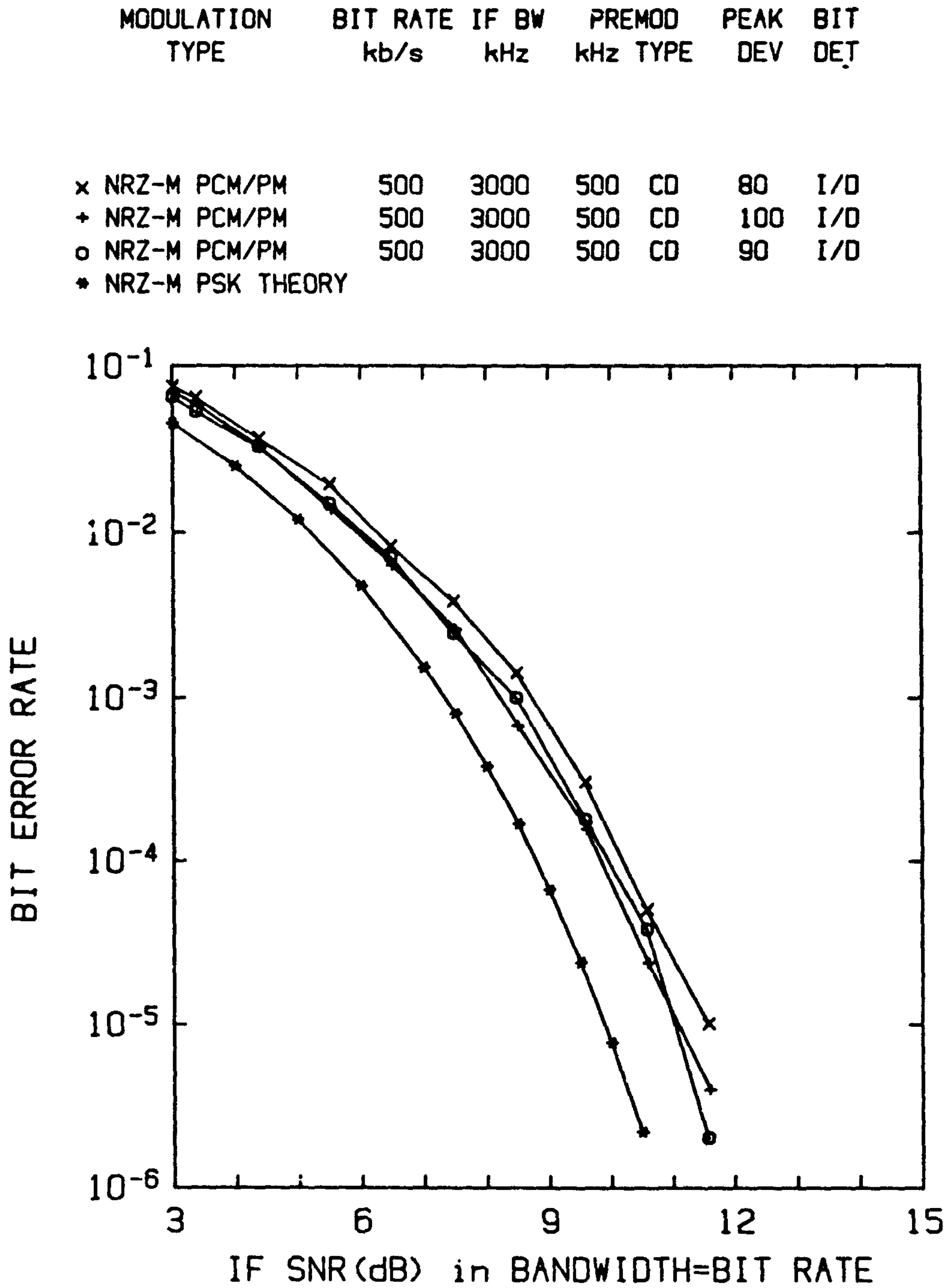


Figure 54. BER for 80, 90 and 100 Degrees Peak DEV (NRZ-M).

MODULATION TYPE	BIT RATE kb/s	IF BW kHz	PREMOD kHz	PREMOD TYPE	PEAK DEV	BIT DET
× NRZ-M PCM/PM	500	3000	350	CD	80	I/D
+ NRZ-M PCM/PM	500	3000	350	CD	100	I/D
o NRZ-M PCM/PM	500	3000	350	CD	90	I/D
* NRZ-M PSK THEORY						

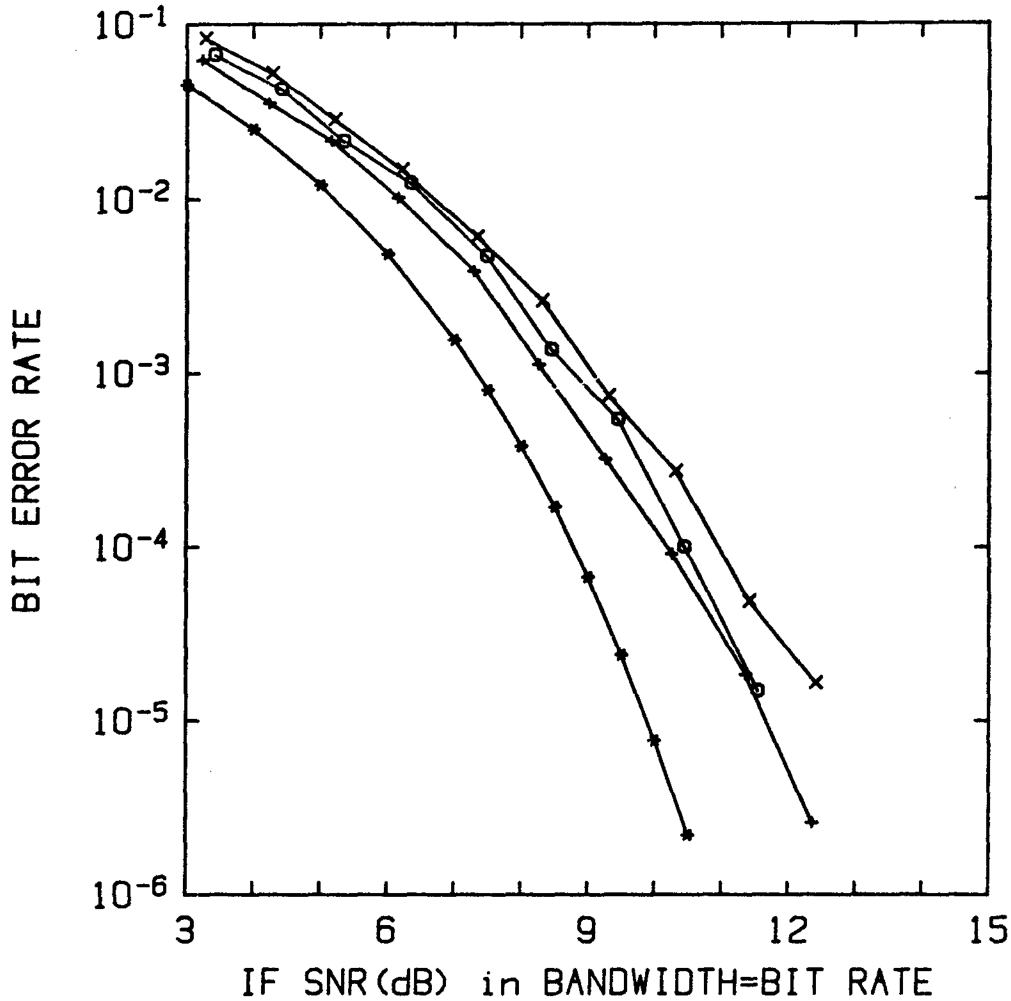


Figure 55. BER for 80, 90 and 100 Degrees Peak DEV (NRZ-M).

MODULATION TYPE	BIT RATE kb/s	IF BW kHz	PREMOD kHz	PREMOD TYPE	PEAK DEV	BIT DET
× NRZ-M PCM/PM	500	3000	350	CD	80	F/S
+ NRZ-M PCM/PM	500	3000	350	CD	100	F/S
0 NRZ-M PCM/PM	500	3000	350	CD	90	I/D
* NRZ-M PCM/PM	500	3000	350	CD	90	F/S
o NRZ-M PSK THEORY						

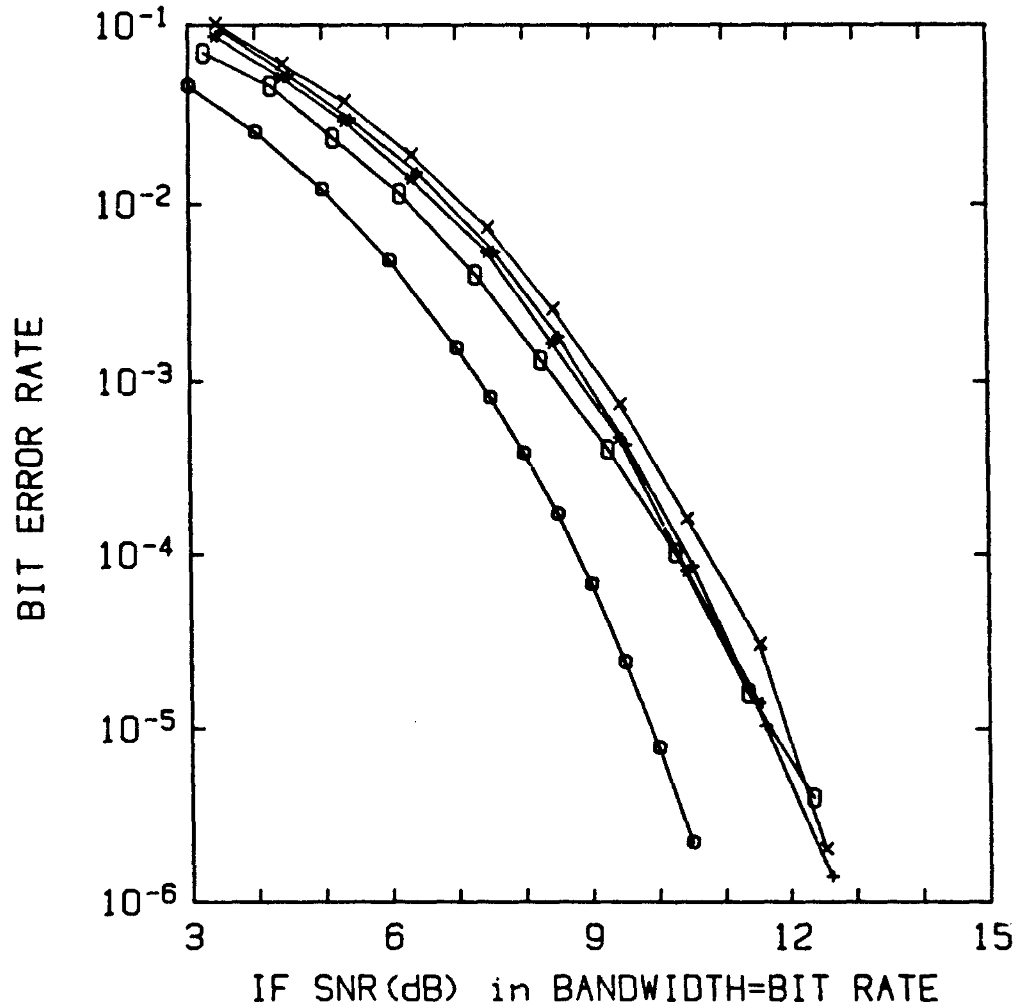


Figure 56. BER for 80, 90 and 100 Degrees Peak DEV (NRZ-M).

apparent difference in the BER performance of PSK demodulator A with either 90 or 100 degrees peak deviation. PSK demodulator B appears to have a slightly lower BER with 100 degrees of peak deviation than with 90 degrees. The performance with 80 degrees of peak deviation is worse than with the other two deviations. The reason for this is that the premodulation filtering of the data reduces the energy in the single bits and therefore a higher deviation is required to make them closer to antipodal.

Selection of Premodulation Filter

The best classical low pass premodulation filter to be used with NRZ PCM/PM ($\pm 90^0$) is a linear phase filter with the widest bandwidth which allows the RF spectral occupancy requirements to be met. The reason for selecting a filter with the widest bandwidth is that premodulation filtering decreases the signal energy per bit without affecting the noise. Table 5 presents the IF SNR in a bandwidth equal to the bit rate required to achieve a BER of 1×10^{-5} for several different premodulation filter bandwidths. The extra SNR required to achieve a BER of 1×10^{-5}, with a bit rate of 500 kb/s and a 3300-kHz IF bandwidth as compared to no premodulation filtering, is 0.5 dB with a 500-kHz linear phase premodulation filter and 1.6 dB with a 250-kHz linear phase premodulation filter. The linear phase premodulation filters cause 0.2 to 0.3 dB less degradation than the constant amplitude filters.

Transversal filters are frequently used in satellite communication systems to minimize the RF spectral occupancy and bit error rate. However, transversal filters will not be discussed in this report.

Table 5. IF SNR (dB) for 10^{-5} BER With NRZ-M PCM/PM and Various Combinations of Bit Rate, Peak Deviation, IF Bandwidth, and Premodulation Filter.

Bit Rate (kb/s)	Peak Deviation (Degrees)	IF Bandwidth (kHz)	Premodulation Filter BW (kHz)	Premodulation Filter Type	IF SNR (dB) in BW=Bit Rate for 10^{-5} BER
300	90	3300	900	CD	10.7
300	90	3300	300	CD	11.4
500	90	3300		None	10.9
500	99	3300		None	11.2
500	90	1500		None	11.1
500	90	1000		None	11.6
500	90	3300	1000	CD	11.1
500	90	3300	1000	CA	11.3
500	90	3300	500	CD	11.4
500	99	3300	500	CD	11.4
500	90	3300	500	CA	11.7
500	90	3300	250	CD	12.5
500	107	3300	250	CD	12.5
500	90	3300	250	CA	12.8

Selection of Receiver IF Bandwidth

The best receiver IF bandwidth is the filter offering the widest bandwidth which rejects all spurious out-of-band signals. The effect of receiver IF bandwidth on BER is illustrated in figure 57. The spurious signals to be rejected include telemetry signals at other center frequencies and, if the signal is to be predetection-recorded, noise that folds over and back across zero hertz when the signal plus noise is mixed with the local oscillator. An example of the second type is when using a 5-MHz IF bandwidth and a 900-kHz predetection record carrier: the noise spectrum at the -3 dB points would extend from f_{IF}-2.5 MHz to f_{IF}+2.5 MHz while the local oscillator frequency would typically be f_{IF}+0.9 MHz. The noise at f_0+1.8 MHz would be translated to 0.9 MHz and be summed with the noise that was translated to 0.9 MHz from f_{IF} MHz. The net result would be to increase the noise power in the region around the predetection carrier frequency by approximately 3 dB; the exact amount of the increase depends upon the shape of the IF filter. The effect is the same as reducing the transmitted power by this amount. Therefore, the receiver IF bandwidth should not be wider than approximately two times the predetection carrier frequency; that is, a 1.8-MHz IF bandwidth for a 900-kHz predetection carrier.

The data presented in figure 58 show an approximate performance improvement of 0.4 dB when using a linear input to the PSK demodulator compared to using a limited input.

Selection of Demodulator Loop Bandwidth

The best loop bandwidth depends on the mission bit rate and the bandwidth of the incidental phase modulation. The loop bandwidth should be wide enough to track out any large amplitude incidental phase modulation. One wideband source of phase modulation is transmission through an ionized gas cloud (plasma). Various rocket booster motors produce ionized gas clouds which cause incidental phase modulation with bandwidths of several kilohertz. However, if the loop bandwidth is wider than approximately 5% of the bit rate, the BER with no incidental phase modulation starts to increase.

Selection of Demodulator Video Bandwidth

The best demodulator video bandwidth is largely determined by the bit detector used (see figure 59). The premodulation filter bandwidth was 1000 kHz for the data in figure 59. The lowest BER was obtained using an integrate and dump bit detector and the widest video filter. The highest BER occurred when a video filter of one-half the bit rate was used in conjunction with the integrate and dump bit detector. The difference in performance was approximately 2 dB at a 10^{-5} BER. When a filter and sample bit detector was selected, the highest BER occurred with the widest video filter. The lowest bit error rates with the filter and sample bit detector were achieved with video filters equal to one-half of the bit rate and the bit rate.

	MODULATION TYPE	BIT RATE kb/s	IF BW kHz	PREMOD kHz TYPE	PEAK DEV	BIT DET
O	NRZ-M PCM/PM LIN	500	1000	1600 RC	90	I/D
o	NRZ-M PCM/PM LIN	500	6000	1600 RC	90	I/D
*	NRZ-M PSK THEORY					

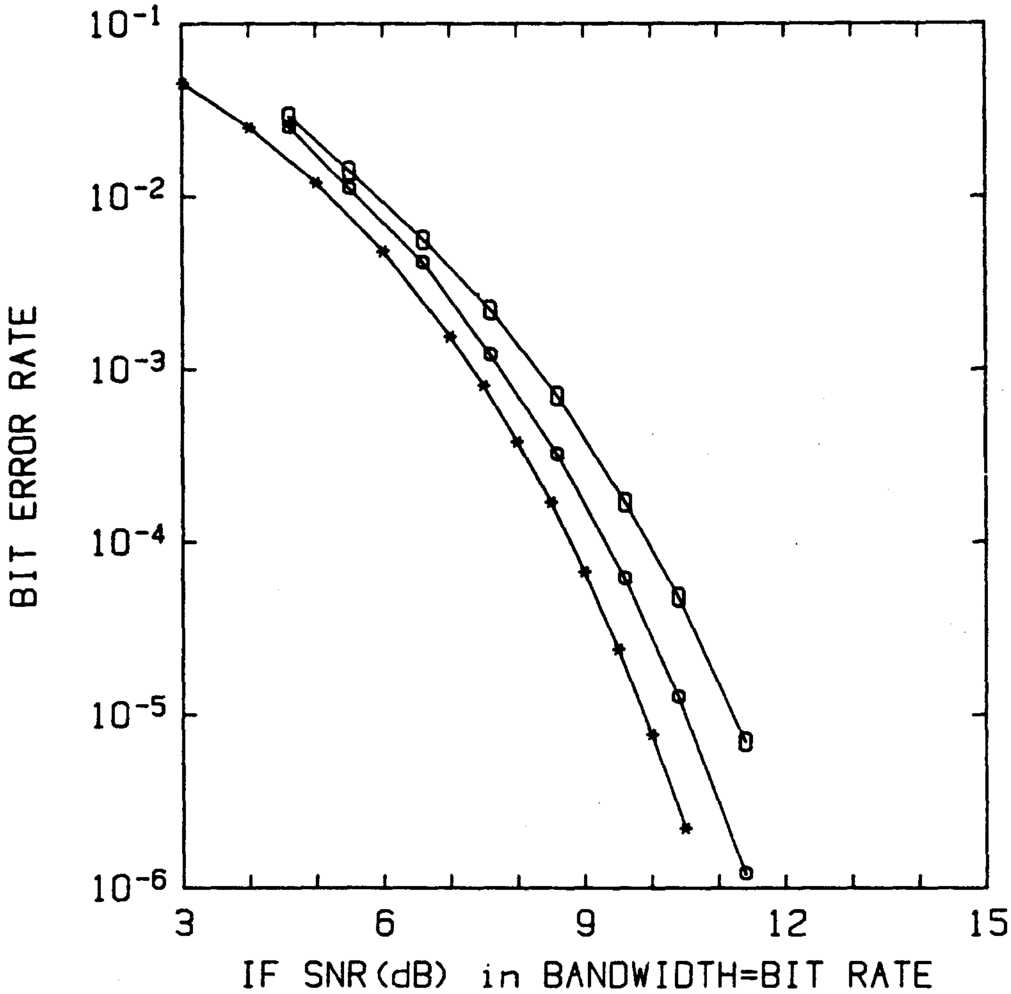


Figure 57. BER for IF BW/Bit Rate=2 and 12.

MODULATION TYPE	BIT RATE kb/s	IF BW kHz	PREMOD kHz	TYPE	PEAK DEV	BIT DET
O NRZ-M PCM/PM LTD	500	6000	1600	RC	90	I/D
o NRZ-M PCM/PM LIN	500	6000	1600	RC	90	I/D
* NRZ-M PSK THEORY						

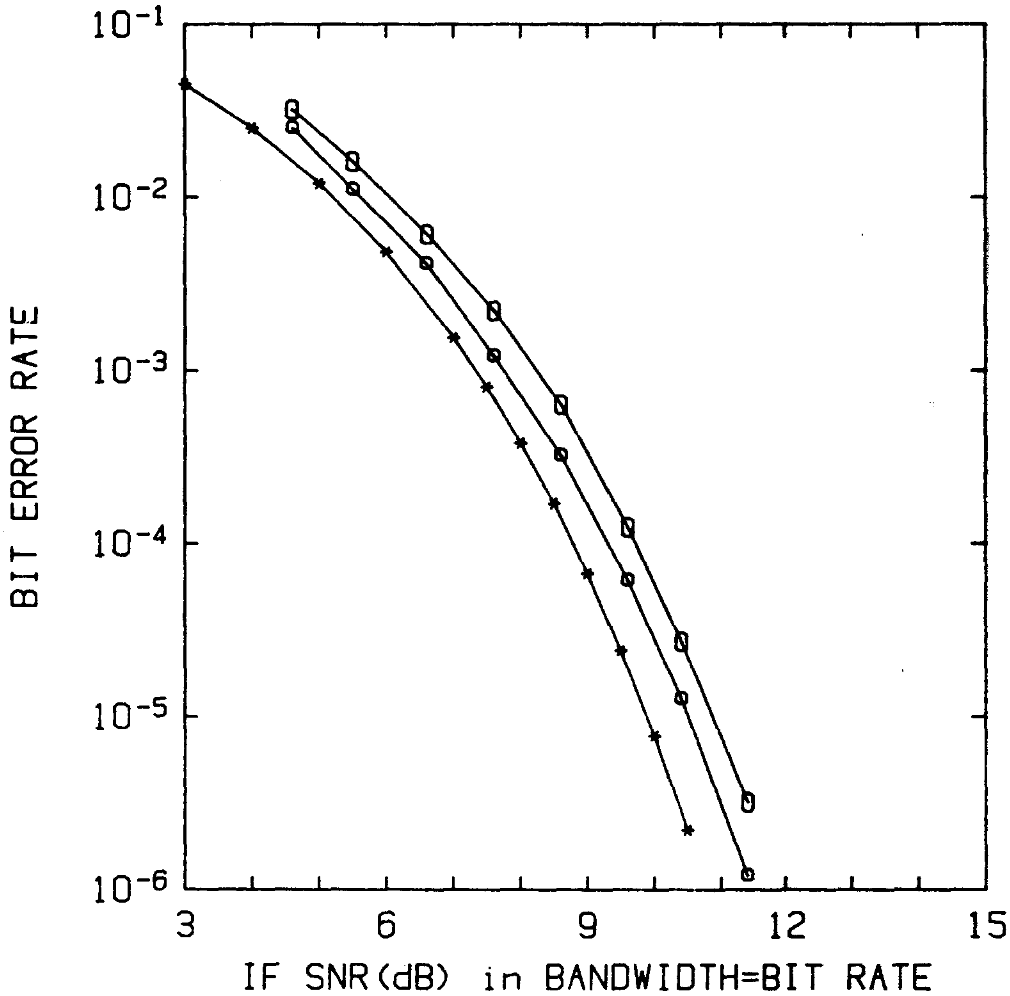


Figure 58. BER for Linear and Limited IF Signals.

MODULATION TYPE	BIT RATE kb/s	IF BW kHz	VIDEO BW kHz	PEAK DEV	BIT DET
+ NRZ-M PCM/PM	500	4000	250	90	F/S
x NRZ-M PCM/PM	500	4000	250	90	I/D
X NRZ-M PCM/PM	500	4000	500	90	F/S
0 NRZ-M PCM/PM	500	4000	500	90	I/D
o NRZ-M PCM/PM	500	4000	1000	90	F/S
* NRZ-M PCM/PM	500	4000	1000	90	I/D

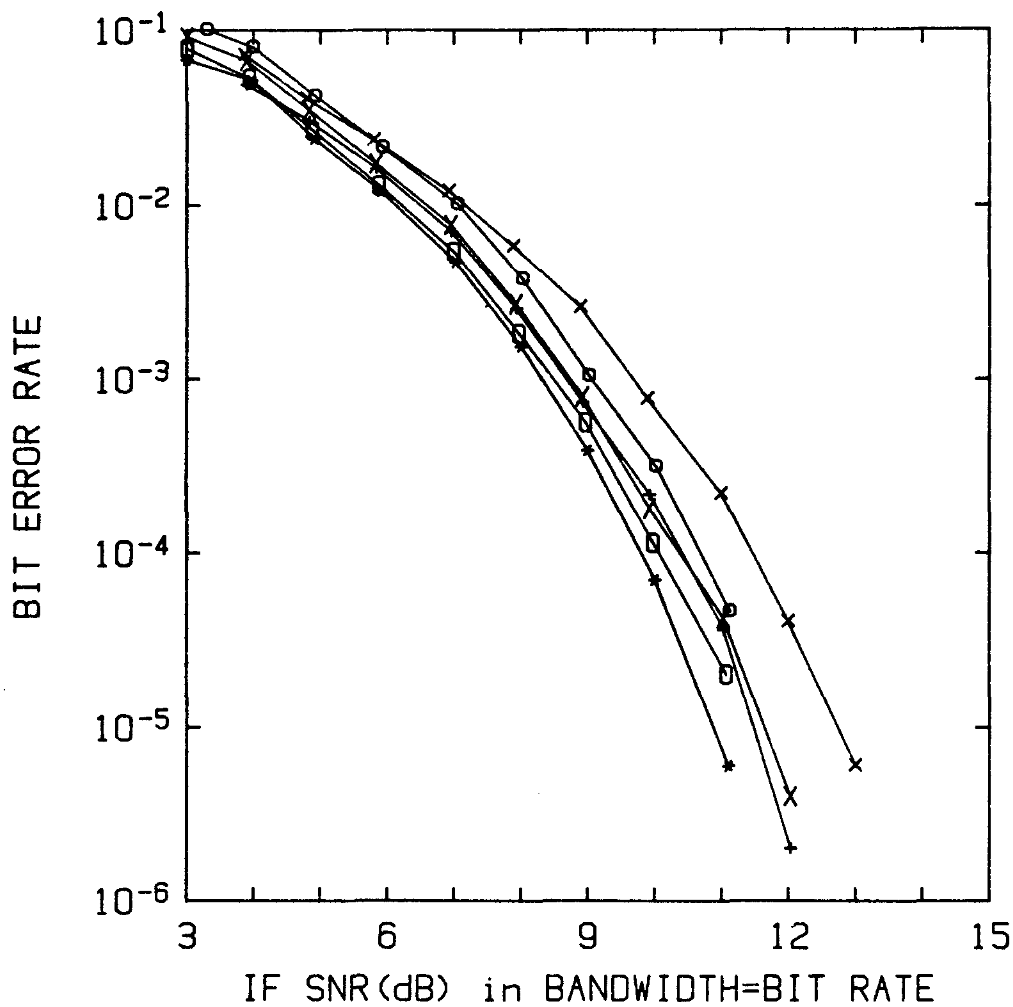


Figure 59. BER for Video BW/Bit Rate=0.5, 1 and 2.

Selection of PCM Bit Synchronizer Bit Detector

The best PCM bit synchronizer bit detector when using NRZ PCM/PM ($\pm 90^{0}$) depends on the amount of filtering performed on the signal prior to the bit synchronizer. When the premodulation and video filter are wider than a value corresponding to the bit rate and the IF bandwidth is set to a value which is equal to at least twice the data bit rate, then the integrate and dump (I/D) bit detector will probably provide the lower bit error rate. When the bandwidth of the premodulation and/or video filters are narrower than 0.7 times the data bit rate and/or the IF bandwidth is less than 1.4 times the bit rate, the filter and sample (F/S) bit detector will probably provide the lower bit error rate. If the total filtering is unknown or is between the values previously stated, then the I/D bit detector is probably the better choice. This is illustrated in figure 59. When the narrowest filter is twice the bit rate, the I/D detector performs approximately 1 dB better than the F/S detector at BERs between 10^{-4} and 10^{-5}. When the narrowest filter is one-half the bit rate, the F/S detector performs approximately 1 dB better than the I/D detector.

RF Spectra and Carrier Level

The optimum peak deviation for unfiltered NRZ PCM/PM is 90 degrees. This deviation produces a carrier null (see figures 60, 61, and 62). As the bit rate is increased from 50 kb/s to 500 kb/s and 800 kb/s, the depth of the carrier null decreases and discrete frequency components appear in the spectrum. These components are caused by the finite rise and fall times of the PCM bit stream and the finite bandwidth of the phase modulator in the RF generator. When a premodulation filter is used, a peak deviation of 90 degrees will no longer produce a carrier null (refer to figure 63). The peak deviation required to produce a carrier null depends on the premodulation filter bandwidth, the filter type and number of poles, as well as the bit pattern of the PCM data. When using a 2047-bit pseudo-noise bit stream at 800 kb/s and an 800-kHz 5-pole linear phase premodulation filter, the minimum carrier level occurs at a peak deviation of 99 degrees (refer to figure 64). A different peak deviation produces the minimum carrier level for other bit patterns for this bit rate and filter. For example, with a bit pattern containing all ones and an NRZ-M code, the carrier is only suppressed 10.6 dB for a peak deviation of 90 degrees (refer to figure 65), but is suppressed by 30.4 dB for a peak deviation of 111 degrees (refer to figure 66). This is the maximum suppression for any deviation under the conditions stated above. However, when the bit pattern is changed to a 2047-bit pseudo-noise sequence, the carrier is only suppressed by 11 dB for a peak deviation of 111 degrees (refer to figure 67). The attenuation of 11 dB is less than the 11.4 dB of carrier suppression produced for a peak deviation of 90 degrees under these conditions. With a 400-kHz 5-pole linear phase premodulation filter, the carrier is suppressed 8.6 dB (refer to figure 68) for a peak deviation of 90 degrees with a 2047-bit pseudo-noise sequence. The minimum carrier level occurs with a peak deviation of 113 degrees under the above conditions (refer to figure 69). Figures 70 and 71 show the RF spectra with constant amplitude premodulation filters.

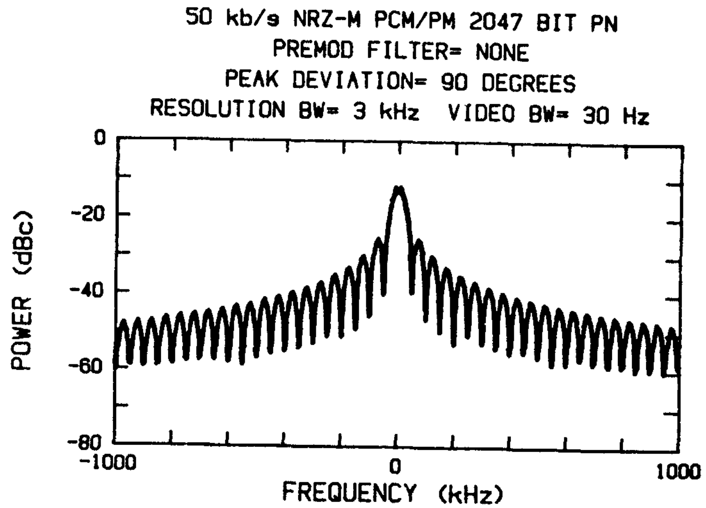


Figure 60. RF Spectrum 50 kb/s NRZ-M PCM/PM

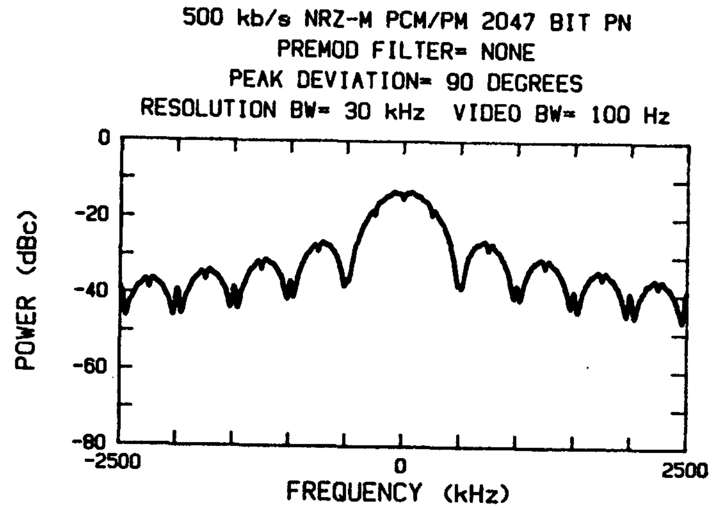


Figure 61. RF Spectrum 500 kb/s NRZ-M PCM/PM

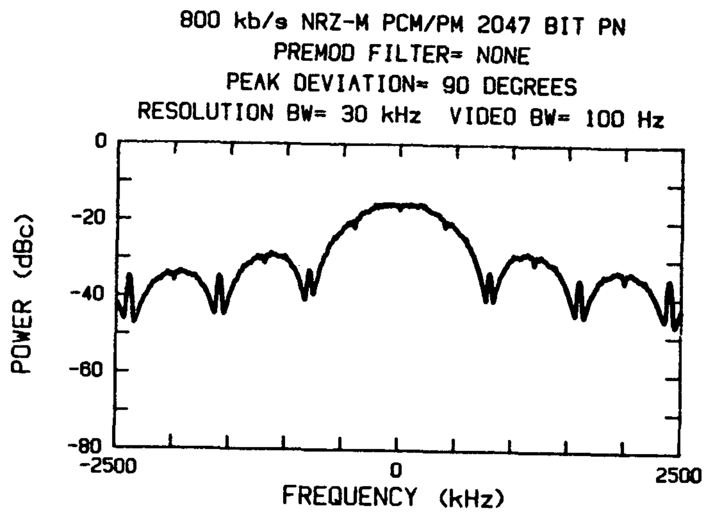


Figure 62. RF Spectrum 800 kb/s NRZ-M PCM/PM

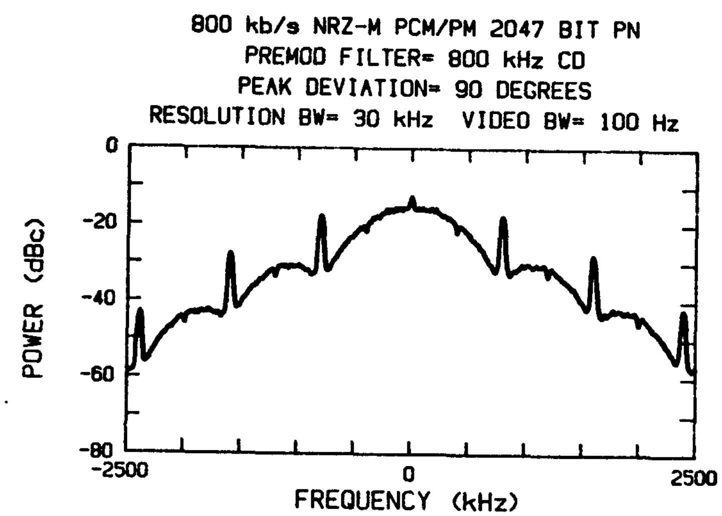


Figure 63. RF Spectrum PREMOD=800 kHz CD Peak DEV=90 Degrees

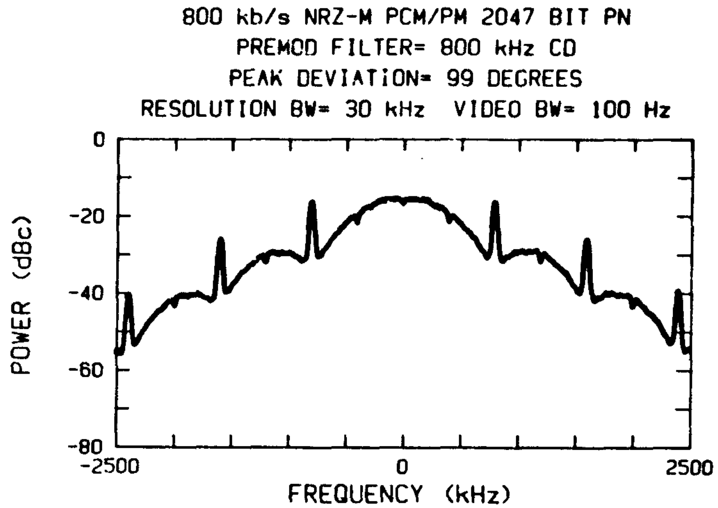


Figure 64. RF Spectrum PREMOD=800 kHz CD Peak DEV=99 Degrees.

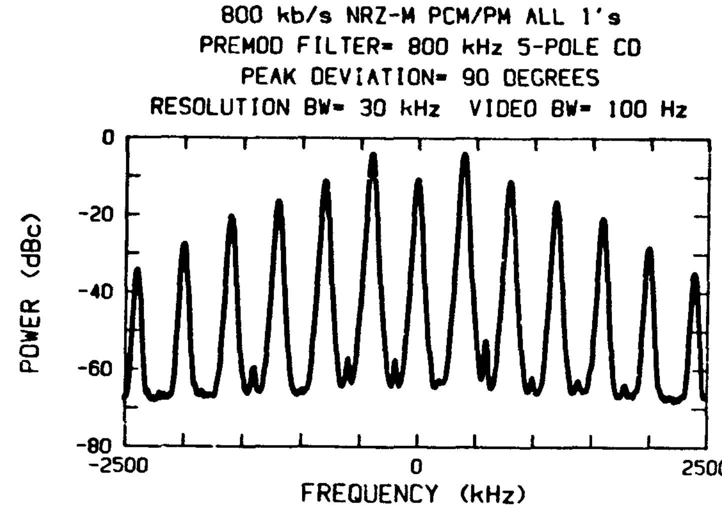


Figure 65. RF Spectrum PREMOD=800 kHz CD Peak DEV=90 Degrees (1s).

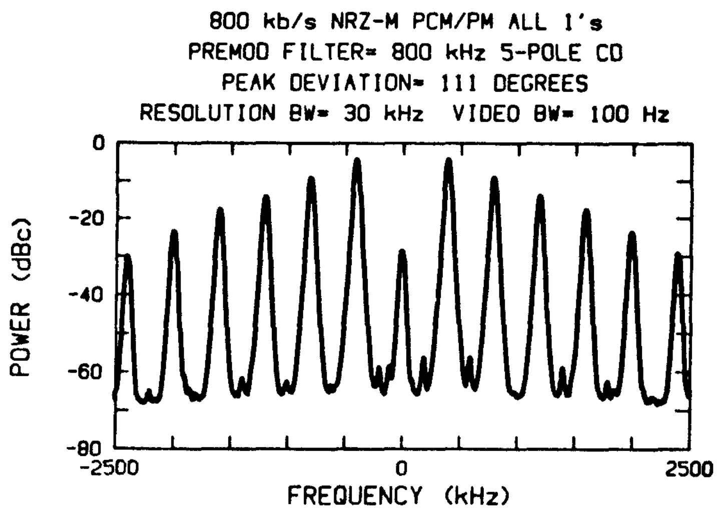


Figure 66. RF Spectrum PREMOD=800 kHz CD Peak DEV=111 DEG (1s).

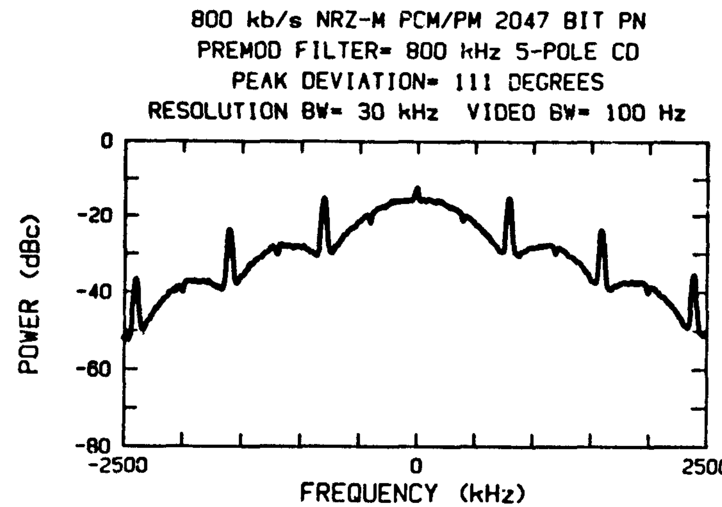


Figure 67. RF Spectrum PREMOD=800 kHz CD Peak DEV=111 Degrees.

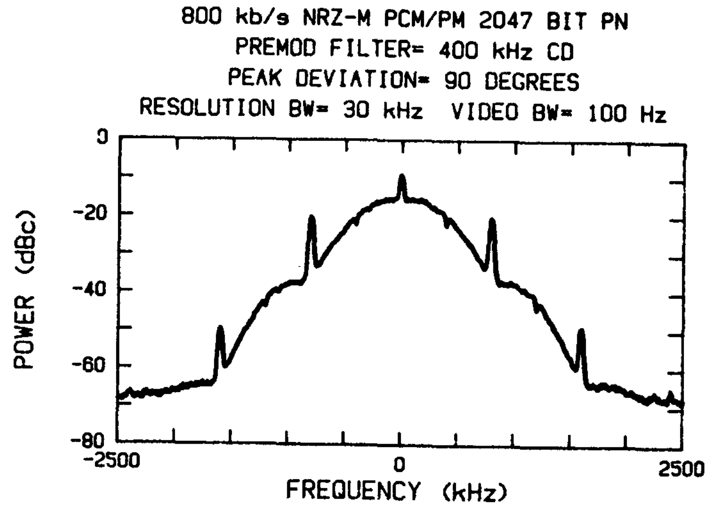


Figure 68. RF Spectrum PREMOD=400 kHz CD Peak DEV=90 Degrees

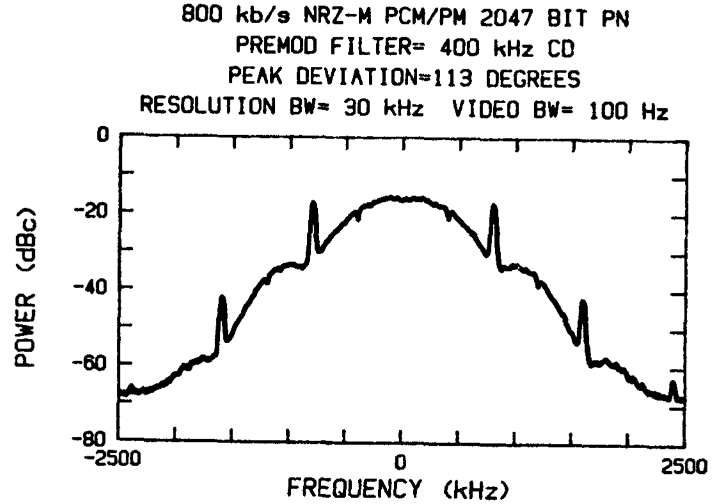


Figure 69. RF Spectrum PREMOD=400 kHz CD Peak DEV=113 Degrees

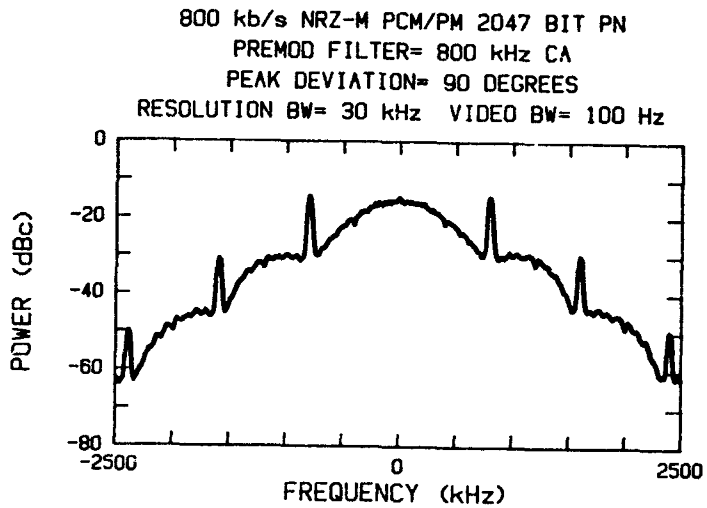


Figure 70. RF Spectrum PREMOD=800 kHz CA Peak DEV=90 Degrees

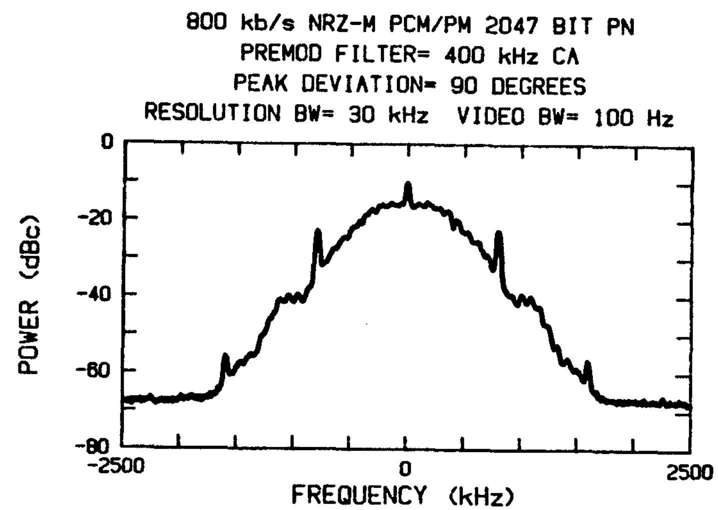


Figure 71. RF Spectrum PREMOD=400 kHz CA Peak DEV=90 Degrees

The RF spectral characteristics of 800 kb/s NRZ-M PCM/PM are presented in table 6 for the spectra of figures 63, 64, 68, and 70. The occupied bandwidth is determined by the spectral spikes and is equal to eight, six, and four times the bit rate for premodulation filters of 800 kHz CD, 800 kHz CA, and 400 kHz CD.

Table 6. RF Spectral Characteristics for 800 kb/s NRZ-M PCM/PM.

Peak Deviation (Degrees)	Premodulation Filter		99% Power Bandwidth		Occupied Bandwidth (kHz)	% of Power in BW = to the Bit Rate
	BW (kHz)	Type	kHz	/Bit Rate		
90	800	CD	2720	3.40	6400	78.7
90	800	CA	2560	3.20	4800	72.6
90	400	CD	1590	1.99	3200	87.2
99	800	CD	3100	3.88	6400	74.6

BIPHASE PCM/PM

Introduction

There are two major types of biphase PCM/PM telemetry signals:

1. Signals with a peak deviation less than 90 degrees.

2. Signals with a peak deviation of approximately 90 degrees.

If the peak deviation is less than 90 degrees, a signal component is always present at the unmodulated carrier frequency. The percentage of the total power contained in this component is determined by the peak deviation, premodulation filtering, phase modulator bandwidth, and the PCM signal bit pattern. If there is no filtering, the remnant carrier power is proportional to $\cos^2(pd)$ and the demodulator output signal power is proportional to $\sin^2(pd)$ where pd is the peak deviation. Table 7 contains a list of relative demodulated signal power and remnant carrier power for several peak deviations with no filtering.

Table 7. Demodulator Signal Output and Remnant Carrier Power as a Function of Peak Deviation.

Peak Deviation (Degrees)	Demodulator Signal Output (dB)	Remnant Carrier Power (dBc)
0	$-\infty$	0
45	-3	-3
60	-1.25	-6
75	-0.3	-11.7
90	0	$-\infty$

If there is sufficient carrier power present, a phase-locked loop (PLL) can be used to track the carrier component and therefore provide a reference signal to the phase demodulator. As the percentage of the total power remaining in the carrier is increased, the demodulated signal amplitude will be reduced proportionately. However, if the carrier component is too small, the PLL will not be able to maintain accurate phase lock at low SNRs. Therefore, a trade-off must be made between carrier power and signal power. Peak carrier deviations between 60 degrees and 75 degrees are usually used for biphase PCM/PM with a carrier-tracking phase demodulator. However, if a premodulation filter bandwidth of twice the bit rate or less is used, peak deviations of 90 degrees can be used successfully with a carrier-tracking demodulator. The carrier is attenuated by approximately 12 dB with a linear phase premodulation filter at twice the bit rate and a peak deviation of 90 degrees (see figure 72). If a peak deviation of 90 degrees is used with a carrier-tracking demodulator, the system designer must make sure that the actual peak deviation cannot produce a carrier null under worst case combinations of deviation sensitivity and bit stream amplitude.

When a peak deviation of approximately 90 degrees is used, a PSK demodulator can be used to demodulate the signal with or without a carrier null. A PSK demodulator reconstructs a carrier signal and uses this signal to coherently detect the modulation. The two most common types of PSK demodulators use a Costas loop or a squaring loop to reconstruct the carrier signal. Both techniques have a 180-degree phase ambiguity problem which means that the polarity (inverted or normal) of the detected signal is unknown. If carrier lock is lost, the detected signal after lock is reacquired has a 50% chance of being inverted compared to the signal before carrier lock was lost. Therefore, the mark and space versions of biphase are usually used when a PSK demodulator is used. The carrier-tracking demodulator does not have a polarity reversal problem and therefore biphase level is usually used in biphase PCM/PM systems when sufficient carrier level is present to allow the demodulator to track the carrier. The bit error rate for biphase level is approximately one-half of the bit error rate for biphase mark and biphase space.

Selection of Peak Deviation

Bit error rate data is presented in figure 73 for peak deviations of 60, 75, and 90 degrees. The bit rate was 500 kb/s, the IF bandwidth was 4000 kHz, and a 1000-kHz 5-pole constant delay premodulation filter was used. This data shows that a 75-degree peak deviation performed about 1.2 dB better than a 60-degree peak deviation under these test conditions. This difference is slightly larger than the 0.95 dB predicted for non-filtered data. The additional degradation is due to the fact that the premodulation filtering reduces the effective amplitude per bit which reduces the effective deviation which causes a reduction in $\sin^2(dp)$. The reduction in $\sin^2(dp)$ is larger for small dp than for large dp with the same proportional reduction in dp.

Comparing biphase level PCM/PM with peak deviations of 75 degrees and 90 degrees, we find that a peak deviation of 90 degrees performs 0.3 to 0.4 dB better than a peak deviation of 75 degrees. The carrier level was -12 dBc with a 90-degree peak deviation and -7 dBc with a 75-degree peak deviation. Therefore, carrier lock will be lost 5 dB sooner with a 90-degree peak deviation than with a 75-degree peak deviation. However, under these test conditions, the PCM bit synchronizer (loop bandwidth of 0.3%) lost lock before a PM demodulator with a 1-kHz loop bandwidth did. A Costas loop demodulator provided the same BER performance as the PM demodulator, but the unknown polarity when using biphase level would present a problem for many applications. Switching to biphase mark causes the BER to approximately double. This is equivalent to a 0.3-dB penalty at a 10^{-5} BER, a 0.5-dB penalty at a 10^{-3} BER, a 0.9-dB penalty at a 10^{-2} BER, and a 2-dB penalty at

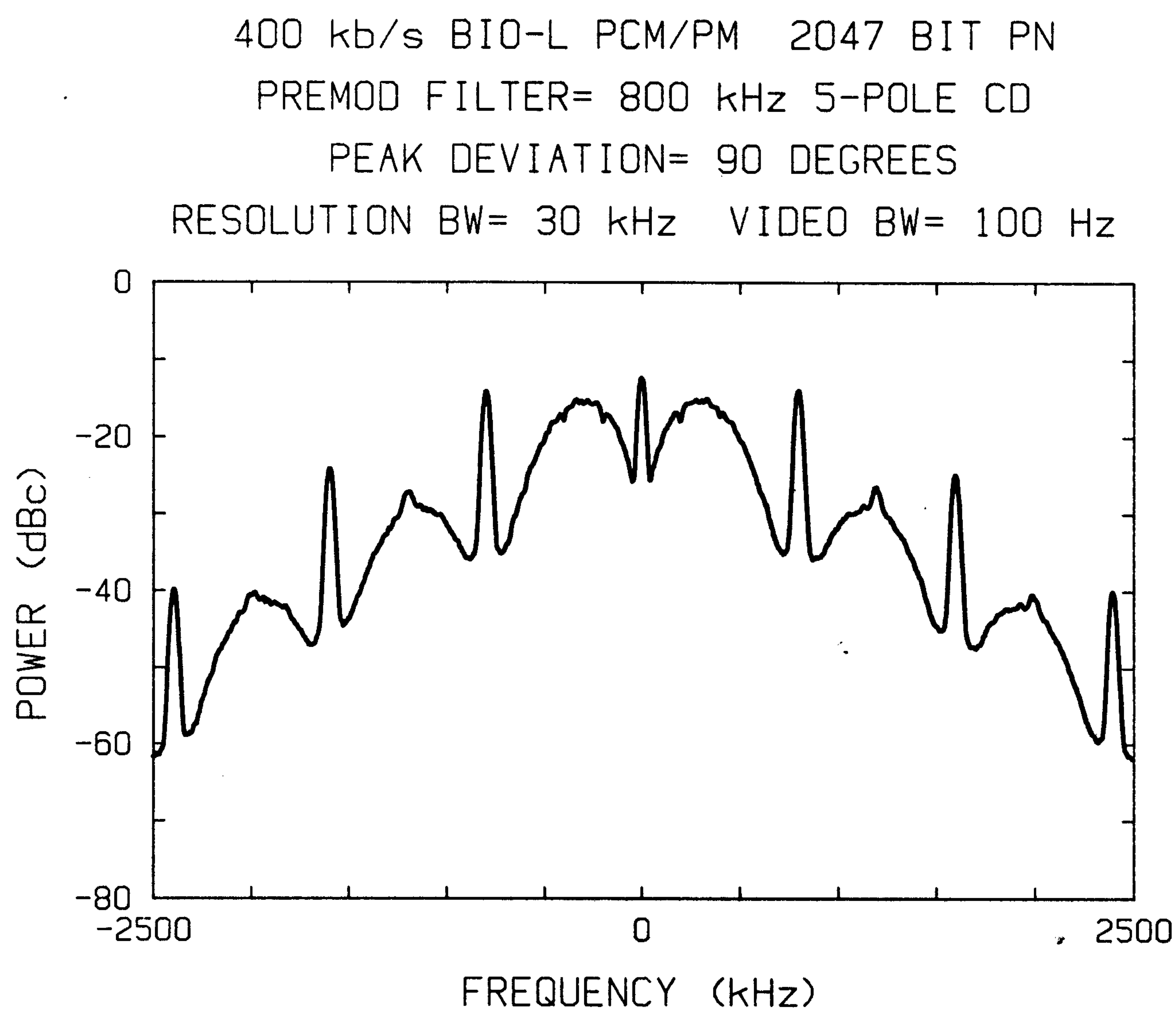


Figure 72. RF Spectrum 400 kb/s Biphase PCM/PM.

MODULATION TYPE	BIT RATE kb/s	IF BW kHz	PREMOD kHz	PREMOD TYPE	PEAK DEV	BIT DET
+ BIO-L PCM/PM	500	4000	1000	CD	60	
0 BIO-L PCM/PM	500	4000	1000	CD	75	
o BIO-L PCM/PM	500	4000	1000	CD	9C	
* BIO-M PCM/PM	500	4000	1000	CD	90	

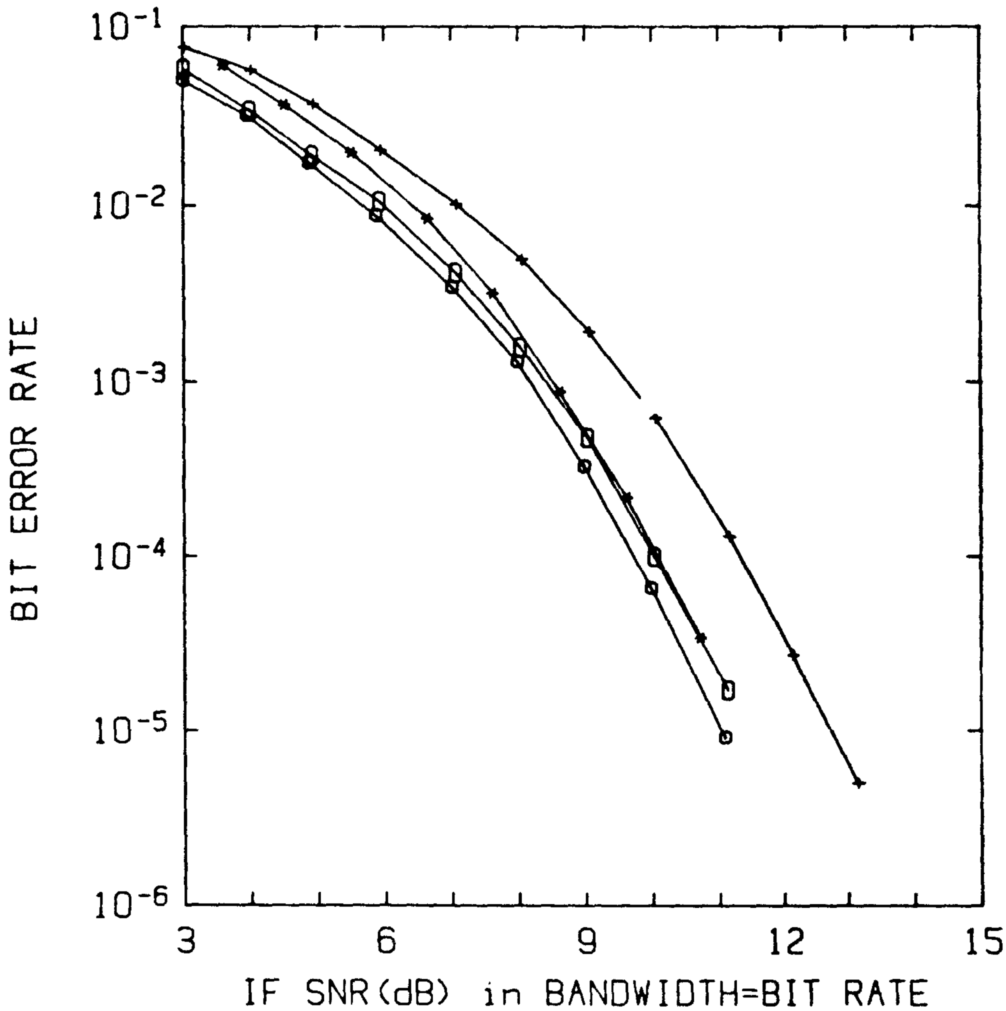


Figure 73. BER for 60, 75 and 90 Degrees Peak DEV.

a BER of 10^{-1}. Therefore, biphase mark with a 90-degree peak deviation should perform much the same as biphase level with a 75-degree peak deviation at a BER of 10^{-5}. This is also shown in figure 73. Biphase level with a 75-degree peak deviation has a measureably lower BER than biphase mark with a 90-degree peak deviation for BERs larger than 10^{-3}.

Bit error rate data is presented in figure 74 for a premodulation filter equal to the bit rate and peak deviations of 60, 75, and 90 degrees. Again, a peak deviation of 75 degrees performs approximately 1.2 dB better than a deviation of 60 degrees. However, under these conditions, a 90-degree peak deviation and biphase level coding perform approximately 1 dB better than a 75-degree peak deviation at a BER of 10^{-5}. A 90-degree peak deviation and biphase mark coding perform better than a 75-degree peak deviation and biphase level coding for BERs less than 10^{-2}.

Selection of Premodulation Filter

The data presented in figures 75, 76, 77, and 78 show that the bit error performance is essentially the same for constant amplitude and constant delay filters having the same bandwidth. These data also show that the BER penalty for using a premodulation filter with a bandwidth equal to the bit rate instead of a premodulation filter equal to twice the bit rate is 1.5 $\pm$0.5 dB when the IF bandwidth is at least three times the bit rate. The penalty is approximately 1.8 dB with a 60-degree peak deviation, 1.5 dB with a 75-degree peak deviation, and 1.0 dB with a 90-degree peak deviation for an IF bandwidth of eight times the bit rate. With an IF bandwidth equal to twice the bit rate, the penalty for using a premodulation bandwidth equal to the bit rate is 1.2 $\pm$0.2 dB. The penalty for using a premodulation filter equal to twice the bit rate is approximately 0.3 dB when compared to no premodulation filtering.

Selection of Receiver IF Bandwidth

The effect of different IF filter bandwidths on the bit error rate is shown in figures 79, 80, and 81. These data show that an IF bandwidth of eight times the bit rate performs approximately the same as an IF bandwidth of twenty times the bit rate. An IF bandwidth of three times the bit rate causes an SNR penalty of approximately 0.5 dB when compared to an IF bandwidth of eight times the bit rate. An IF bandwidth of two times the bit rate causes an SNR penalty of approximately 1.3 dB when compared to an IF bandwidth of eight times the bit rate.

Figure 82 shows a biphase level PCM signal which has been low-pass filtered at twice the bit rate. Figure 83 shows a biphase level PCM eye pattern with a low pass filter at 1.4 times the bit rate.

Selection of Demodulator Loop Bandwidth

The best loop bandwidth is a function of the mission bit rate and the bandwidth of the incidental phase modulation. The loop bandwidth should be wide enough to track out any large amplitude incidental phase modulation. The BER with no incidental phase modulation starts to increase if the loop bandwidth is wider than approximately 2% of the bit rate for a PM demodulator and 5% of the bit rate for a PSK demodulator.

MODULATION TYPE	BIT RATE kb/s	IF BW kHz	PREMOD kHz	PREMOD TYPE	PEAK DEV	BIT DET
+ BIO-L PCM/PM	500	4000	500	CD	60	
0 BIO-L PCM/PM	500	4000	500	CD	75	
o BIO-L PCM/PM	500	4000	500	CD	90	
* BIO-M PCM/PM	500	4000	500	CD	90	

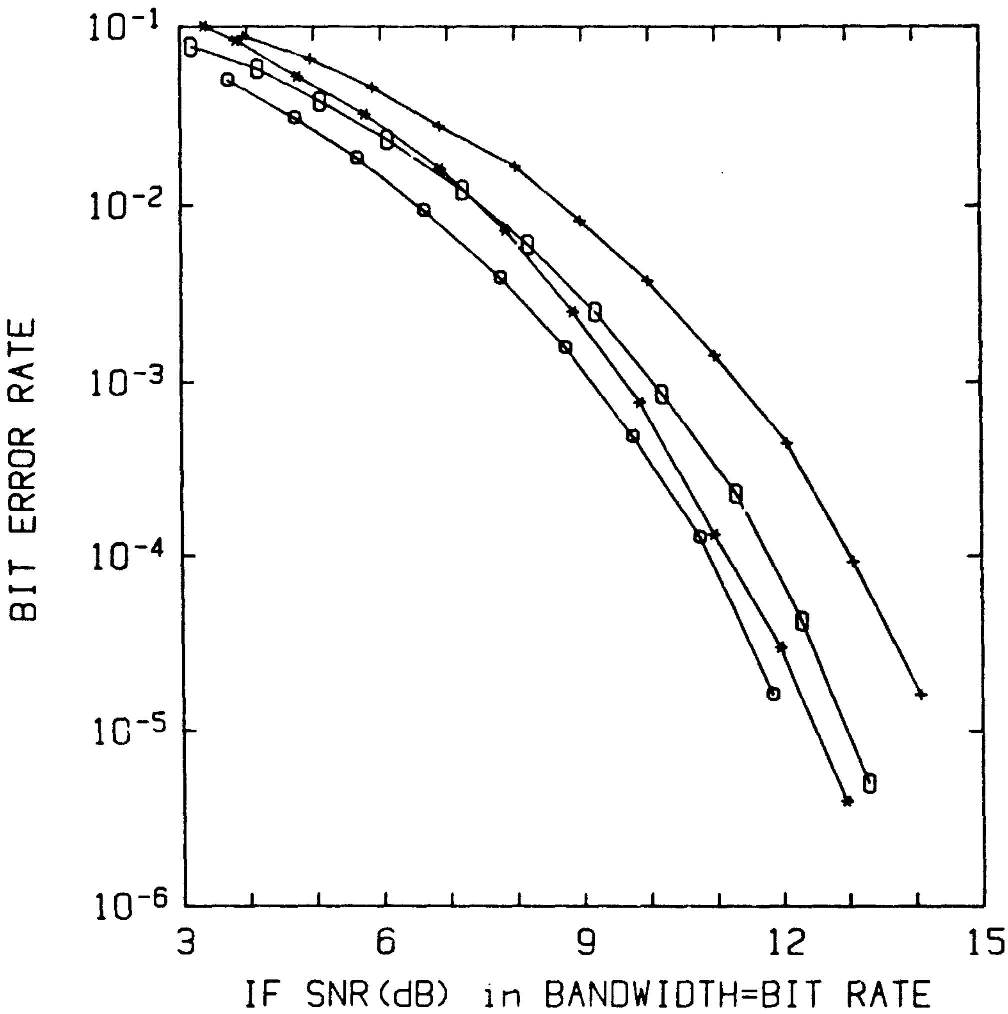


Figure 74. BER for 60, 75 and 90 DEG Peak DEV PREMOD BW=500 kHz.

MODULATION TYPE	BIT RATE kb/s	IF BW kHz	PREMOD kHz	TYPE	PEAK DEV	BIT DET
O BIO-L PCM/PM	500	4000	500	CA	60	
+ BIO-L PCM/PM	500	4000	500	CD	60	
o BIO-L PCM/PM	500	4000	1000	CA	60	
* BIO-L PCM/PM	500	4000	1000	CD	60	

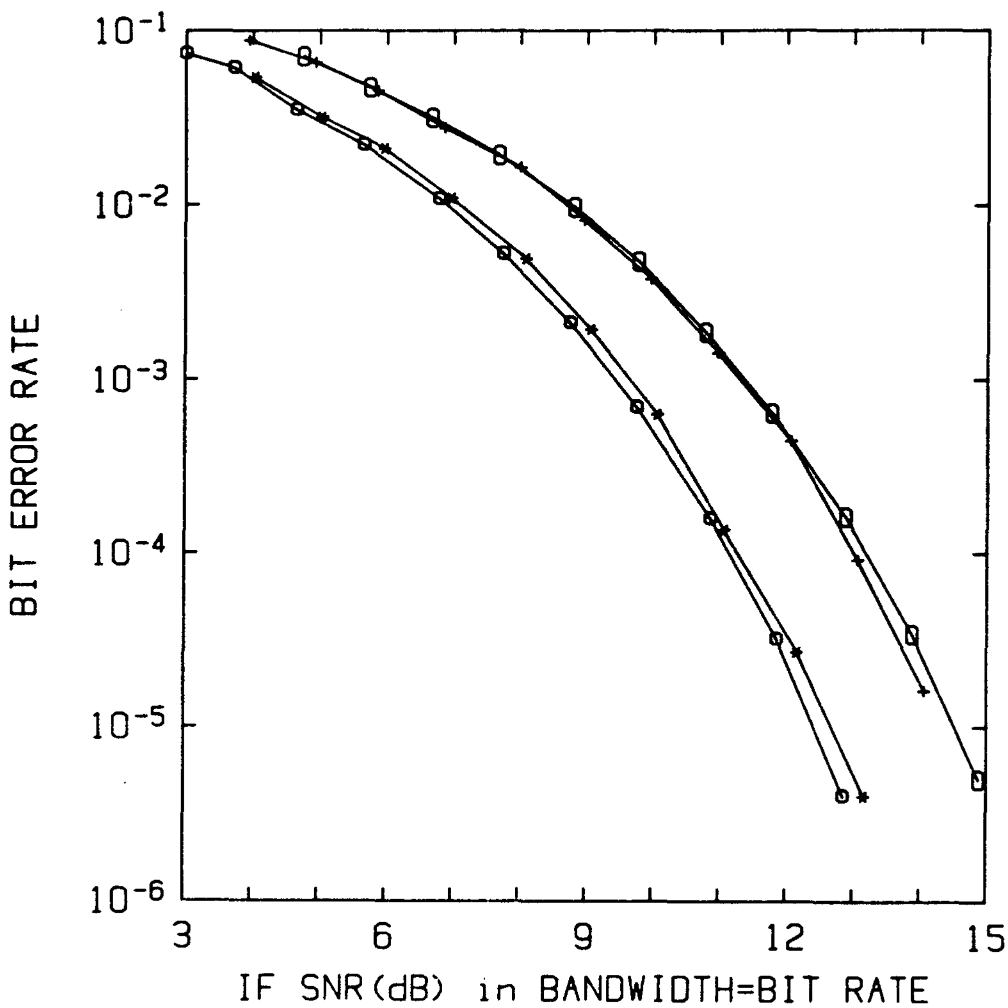


Figure 75. BER for Peak DEV=60 DEG and PREMOD BW=1 and 2 Bit Rate.

MODULATION TYPE	BIT RATE kb/s	IF BW kHz	PREMOD kHz	TYPE	PEAK DEV	BIT DET
O BIO-L PCM/PM	500	4000	500	CA	75	
+ BIO-L PCM/PM	500	4000	500	CD	75	
o BIO-L PCM/PM	500	4000	1000	CA	75	
* BIO-L PCM/PM	500	4000	1000	CD	75	

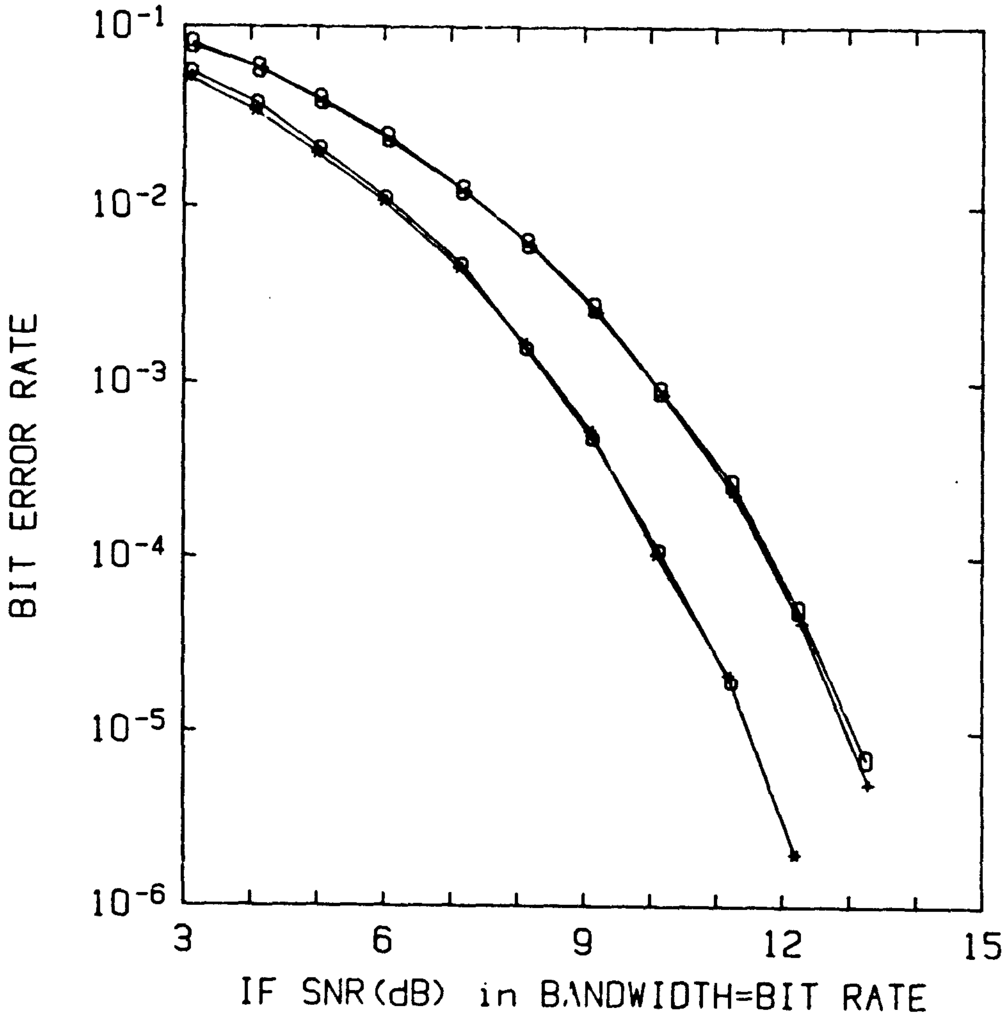
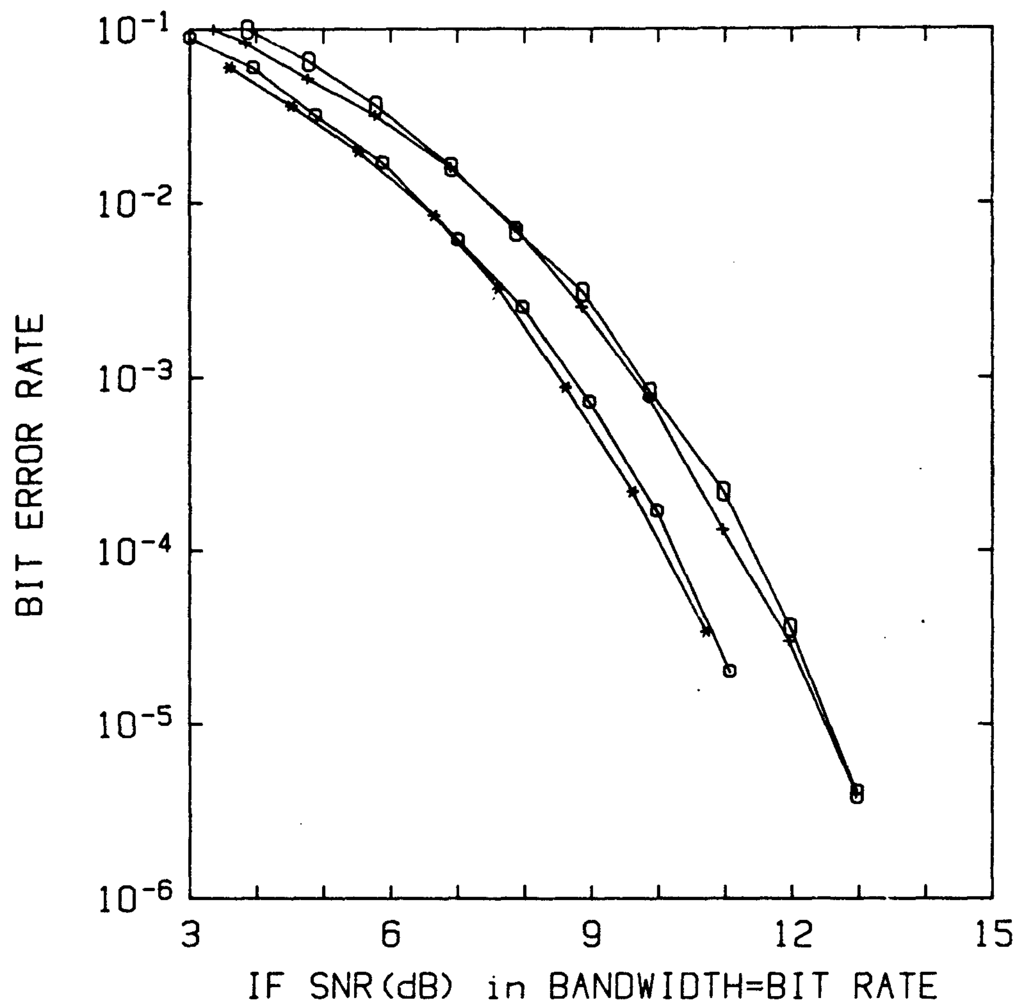


Figure 76. BER for Peak DEV=75 DEG and PREMOD BW=1 and 2 Bit Rate.

MODULATION TYPE	BIT RATE kb/s	IF BW kHz	PREMOD kHz	PREMOD TYPE	PEAK DEV	BIT DET
0 BIO-M PCM/PM	500	4000	500	CA	90	
+ BIO-M PCM/PM	500	4000	500	CD	90	
o BIO-M PCM/PM	500	4000	1000	CA	90	
* BIO-M PCM/PM	500	4000	1000	CD	90	



igure 77. BER for Peak DEV=90 DEG and PREMOD BW=1 and 2 Bit Rate.

MODULATION TYPE	BIT RATE kb/s	IF BW kHz	PREMOD kHz	PREMOD TYPE	PEAK DEV	BIT DET
O BIO-L PCM/PM	500	1500	500	CA	75	
+ BIO-L PCM/PM	500	1500	500	CD	75	
o BIO-L PCM/PM	500	1500	1000	CA	75	
* BIO-L PCM/PM	500	1500	1000	CD	75	

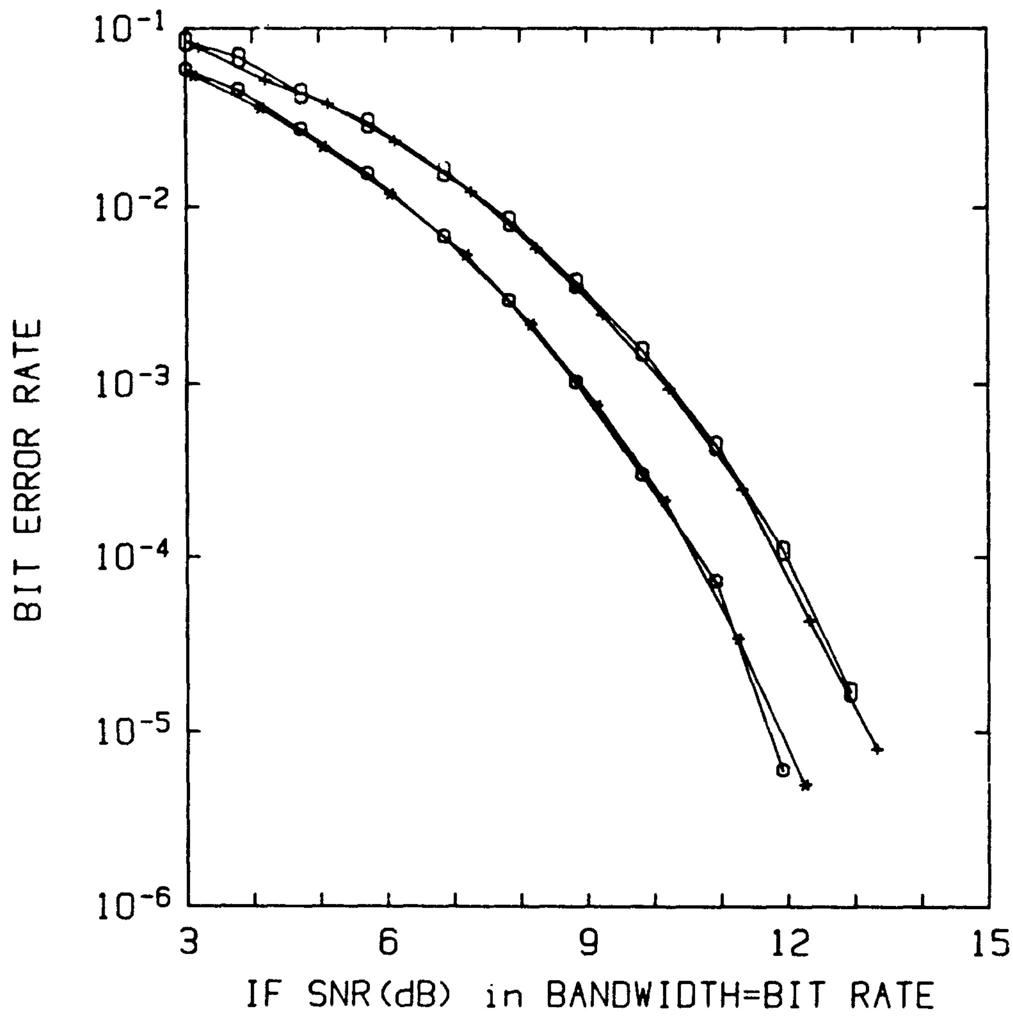


Figure 78. BER for Peak DEV=75 DEG and PREMOD BW=1 and 2 Bit Rate.

MODULATION TYPE	BIT RATE kb/s	IF BW kHz	PREMOD kHz TYPE	PEAK DEV	BIT DET
+ BIO-L PCM/PM	500	1000	1000 CD	60	
o BIO-L PCM/PM	500	1500	1000 CD	60	
* BIO-L PCM/FM	500	4000	1000 CD	60	

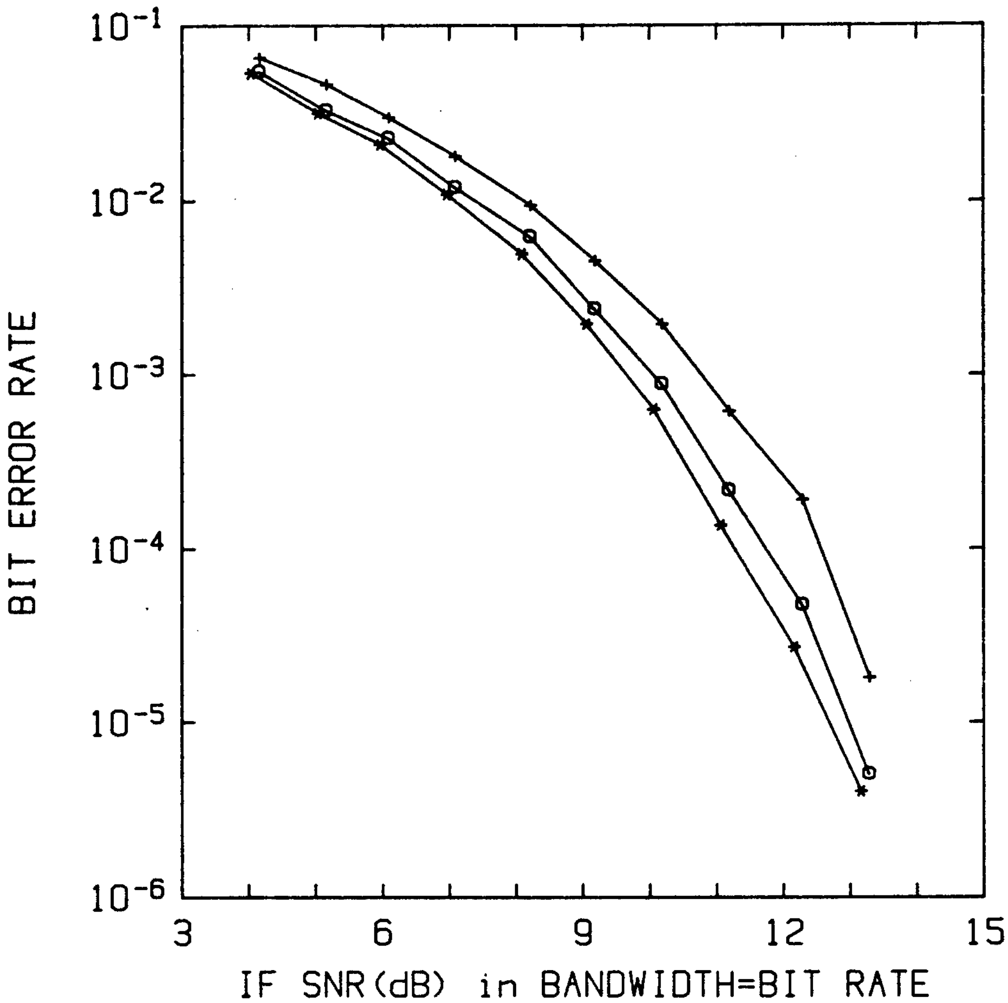


Figure 79. BER for Peak DEV=60 DEG IF BW/Bit Rate=2, 3 and 8.

MODULATION TYPE	BIT RATE kb/s	IF BW kHz	PREMOD kHz TYPE	PEAK DEV	BIT DET
+ BIO-L PCM/PM	500	1000	1000 CD	75	
0 BIO-L PCM/PM	500	1500	1000 CD	75	
o BIO-L PCM/PM	500	4000	1000 CD	75	
* BIO-L PCM/PM	500	10000	1000 CD	75	

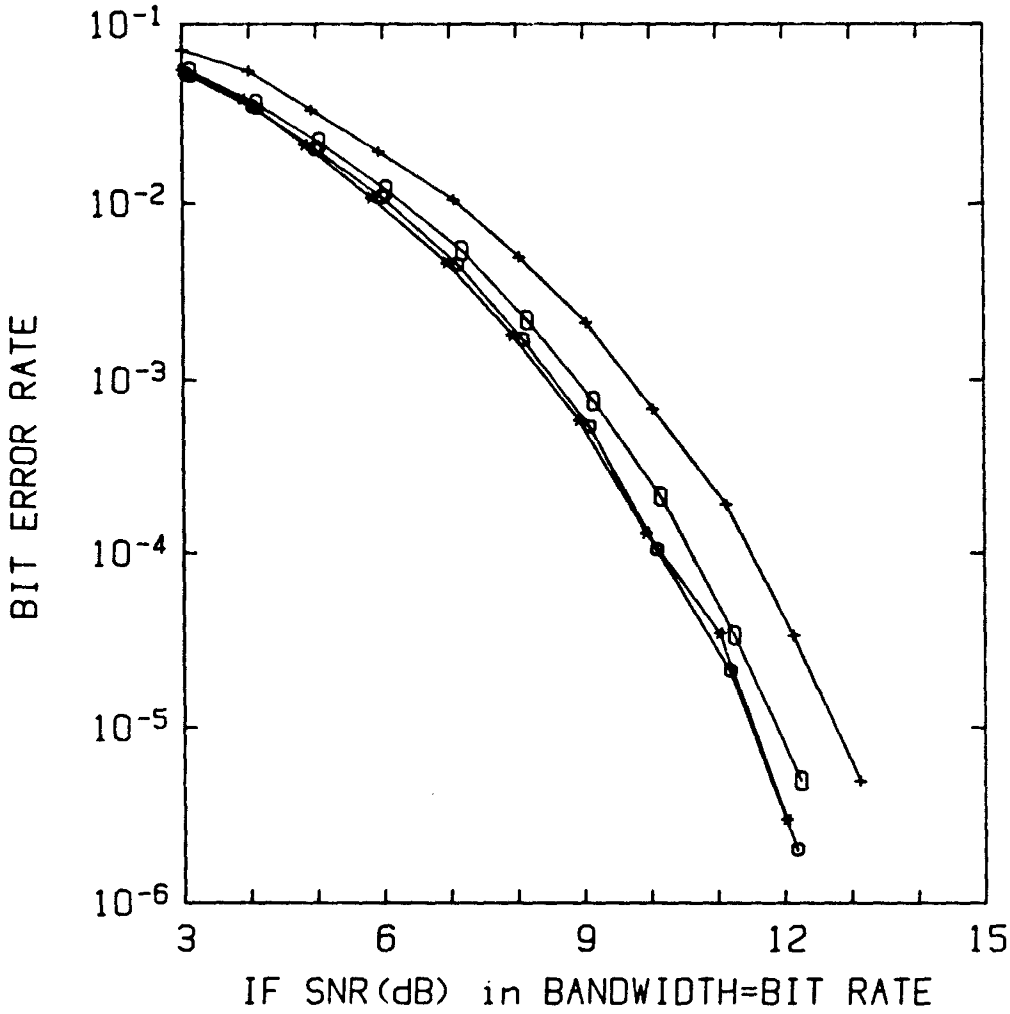


Figure 80. BER for Peak DEV=75 DEG IF BW/Bit Rate=2, 3, 8 and 20.

MODULATION TYPE	BIT RATE kb/s	IF BW kHz	PREMOD kHz	TYPE	PEAK DEV	BIT DET
+ BIO-M PCM/PM	500	1000	1000	CD	90	
0 BIO-M PCM/PM	500	1500	1000	CD	90	
o BIO-M PCM/PM	500	4000	1000	CD	90	
* BIO-M PCM/PM	500	10000	1000	CD	90	

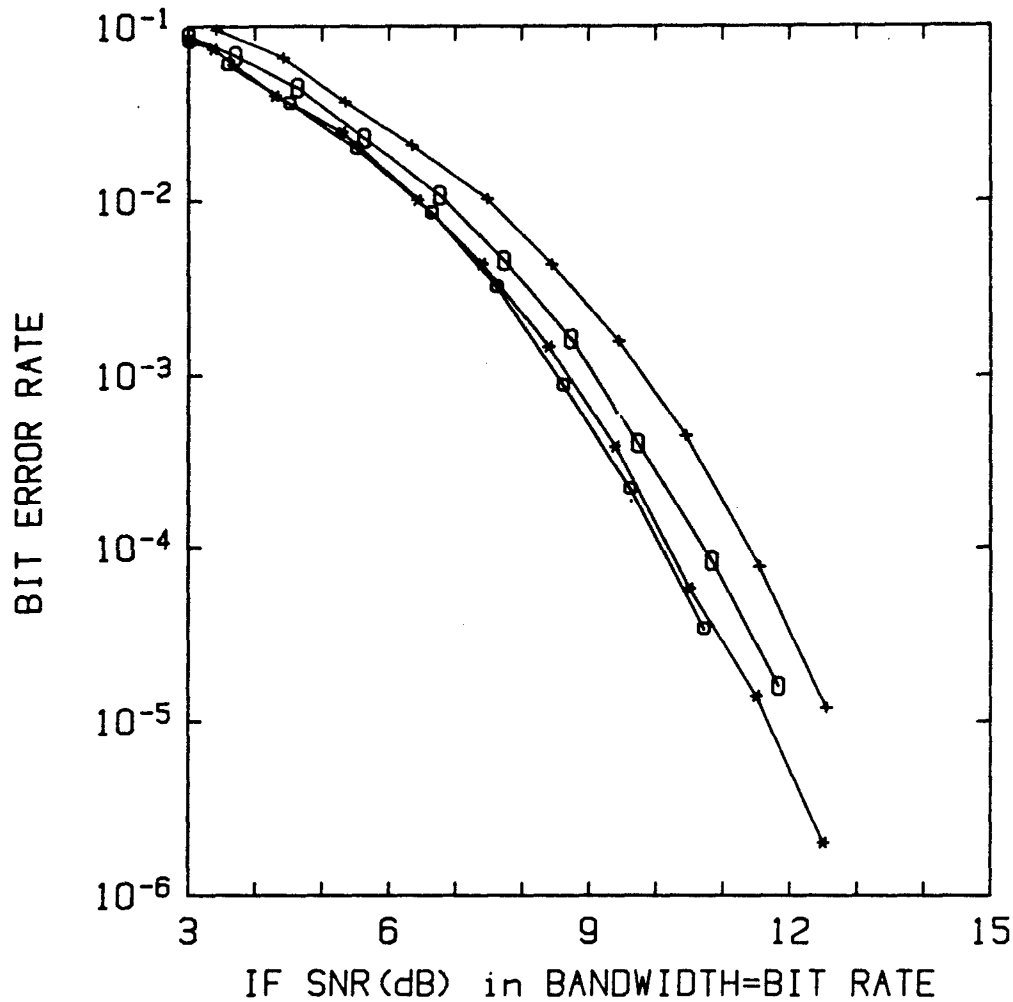


Figure 81. BER for Peak DEV=90 DEG IF BW/Bit Rate=2, 3, 8 and 20.

250 kb/s BIO-L PCM
FILTER=500 kHz 5-POLE LINEAR PHASE

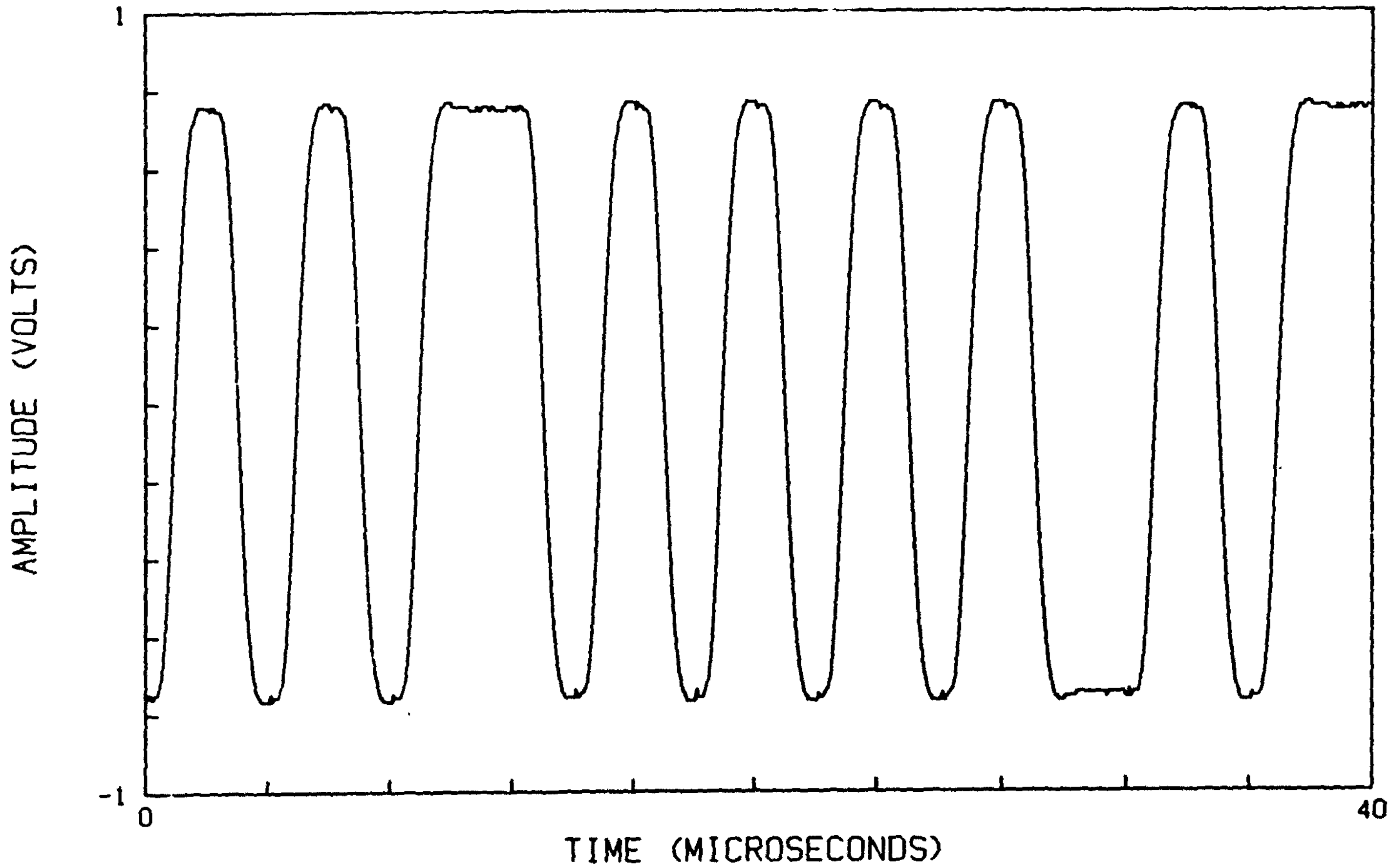


Figure 82. Biphase Signal with PREMOD BW=2 Times Bit Rate (CD).

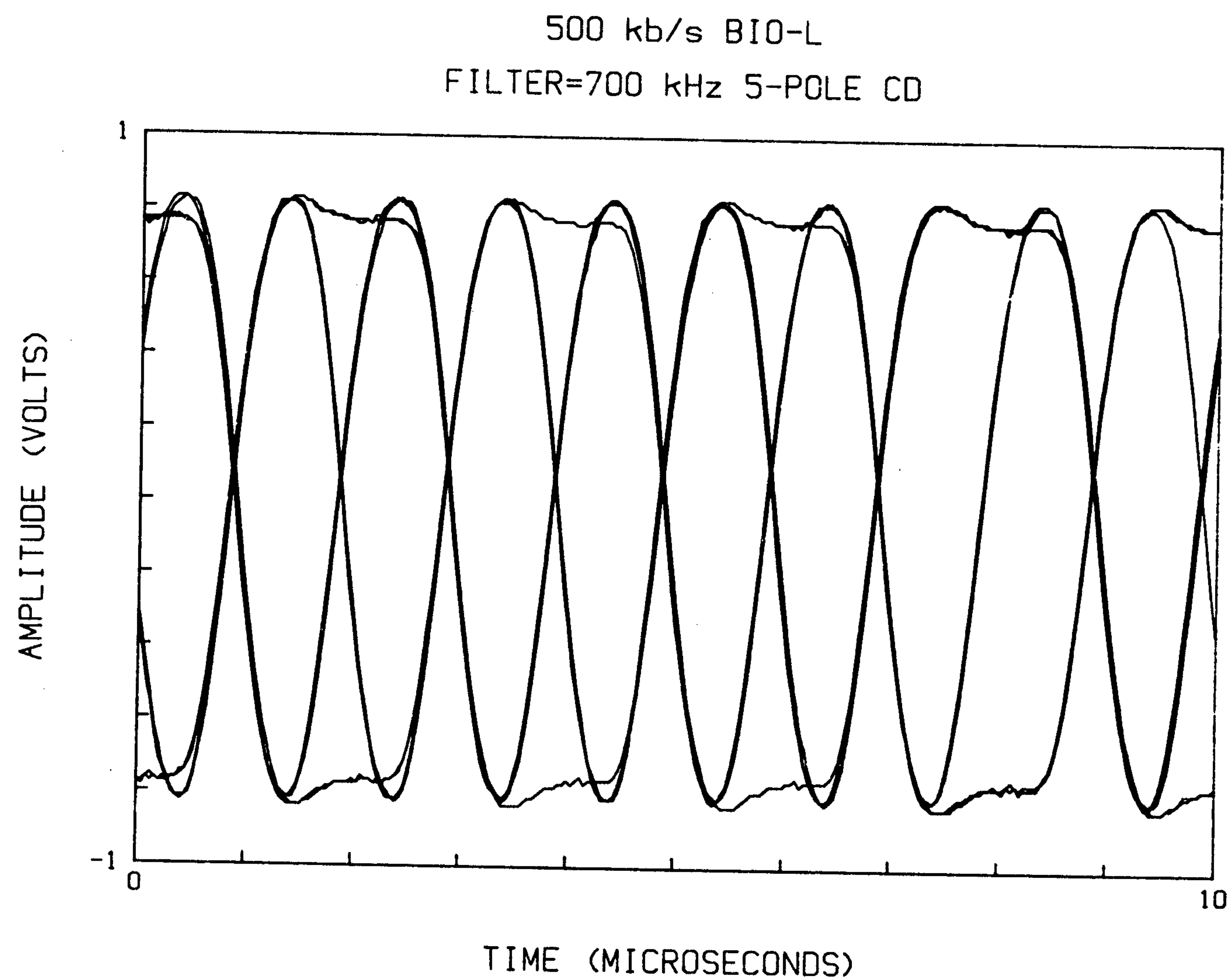


Figure 83. Biphase Eye Pattern with PREMOD BW=1.4 Times Bit Rate.

RF Spectra

Radio frequency spectra are presented in figures 84 through 97 for 400 kb/s pseudo-random biphase PCM/PM with various premodulation filters and peak deviations of 60, 75, and 90 degrees. Figures 84 and 85 show the spectra that result with no premodulation filter. The IRIG criteria of 60 dB below the unmodulated carrier is not met in a 20-MHz bandwidth under these conditions. The data contained in table 8 show that the occupied bandwidth is approximately eight times the bit rate for premodulation filters whose bandwidth is equal to the bit rate and twelve to sixteen times the bit rate for premodulation filters whose bandwidth is equal to twice the bit rate. The sideband levels are higher for larger peak deviations and generally higher with constant delay (CD) premodulation filters than with constant amplitude (CA) premodulation filters.

Table 8. Occupied Bandwidths for 400 kb/s Biphase PCM/PM for Various Peak Deviations and Premodulation Filters.

Peak Deviation (Degrees)	Premodulation Filter		Occupied Bandwidth	
	Bandwidth (kHz)	Type	kHz	/Bit Rate
60	800	CD	4800	12
60	800	CA	3200	8
60	400	CD	3200	8
60	400	CA	3200	8
75	800	CD	4800	12
75	800	CA	4800	12
75	400	CD	3200	8
75	400	CA	3200	8
90	800	CD	6400	16
90	800	CA	6400	16
90	400	CD	3200	8
90	400	CA	3200	8

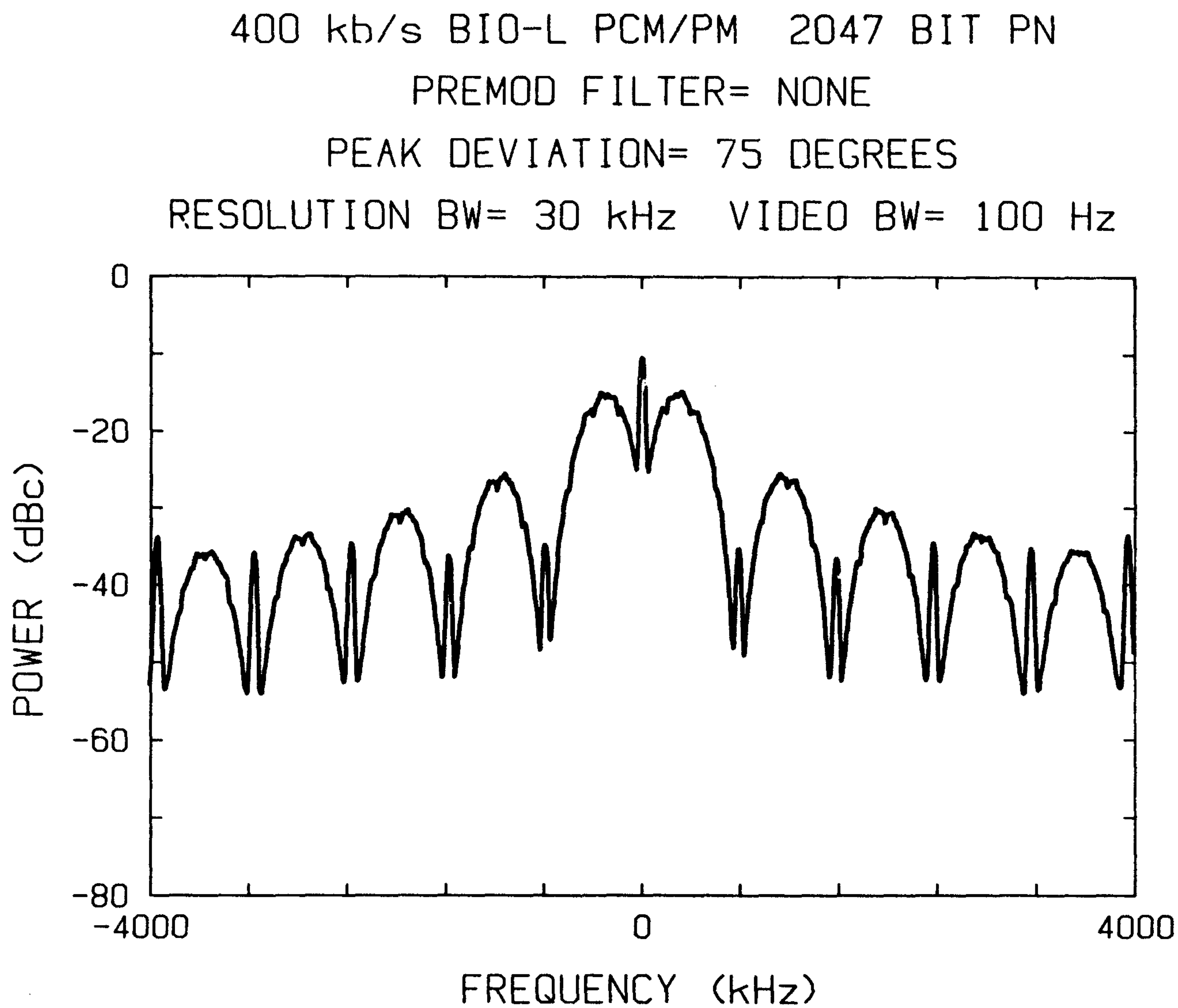


Figure 84. RF Spectrum 400 kb/s Biphase PCM/PM 8 MHz BW.

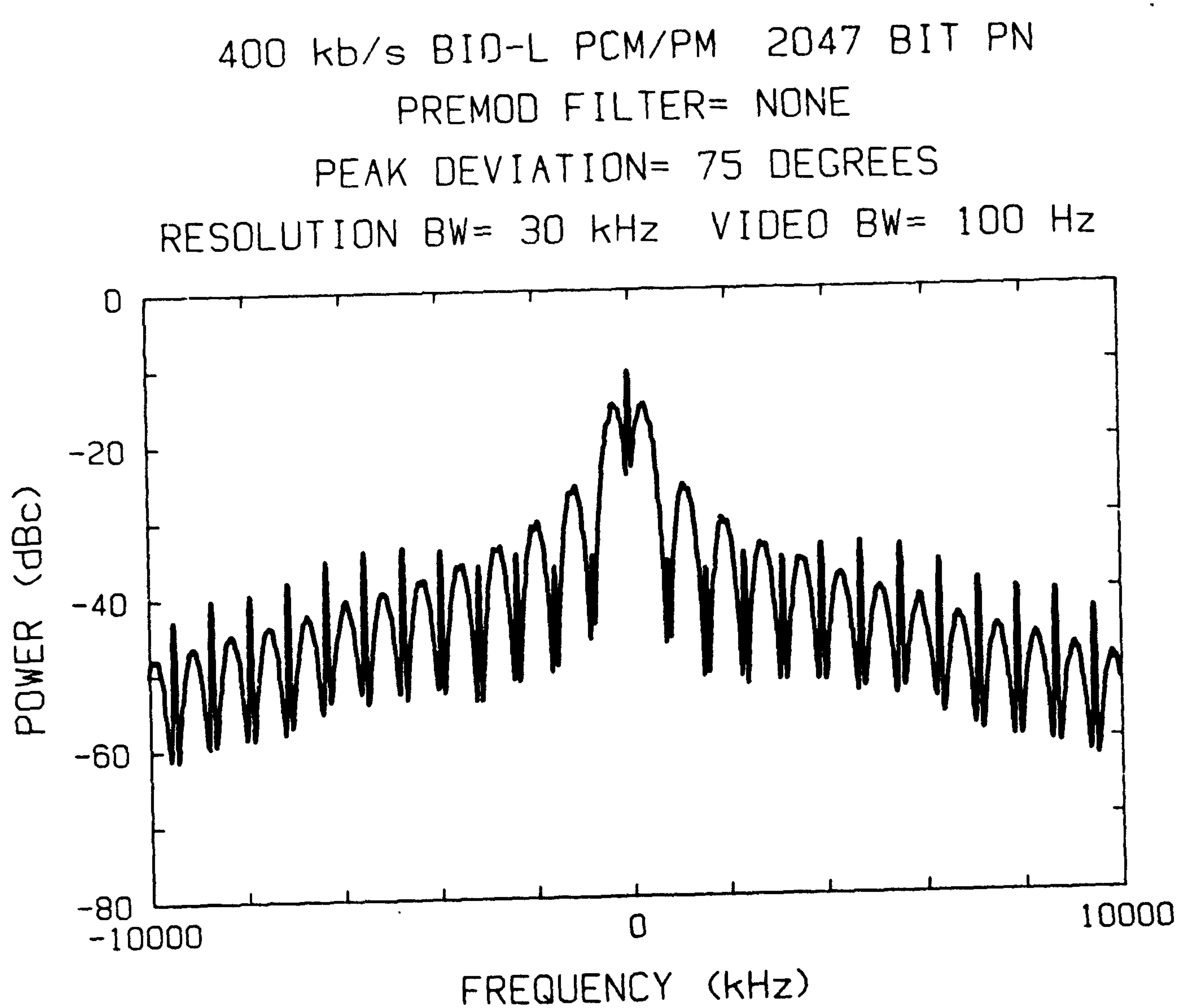


Figure 85. RF Spectrum 400 kb/s Biphase PCM/PM 20 MHz BW.

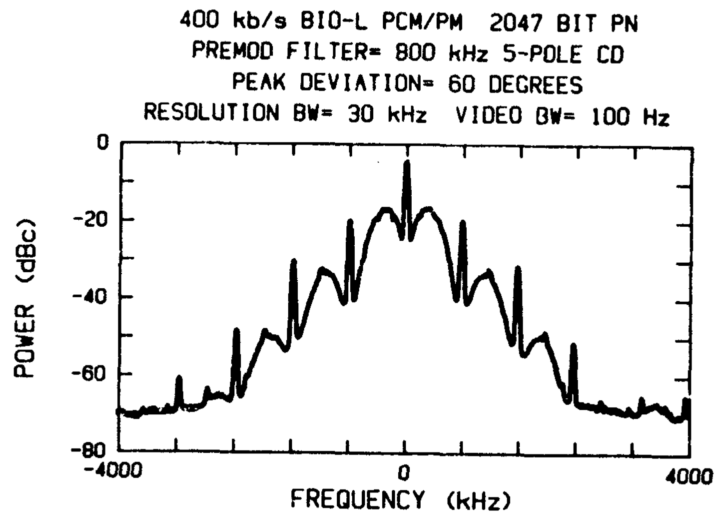


Figure 86. RF Spectrum PREMOD=800 kHz CD Peak DEV=60 Degrees

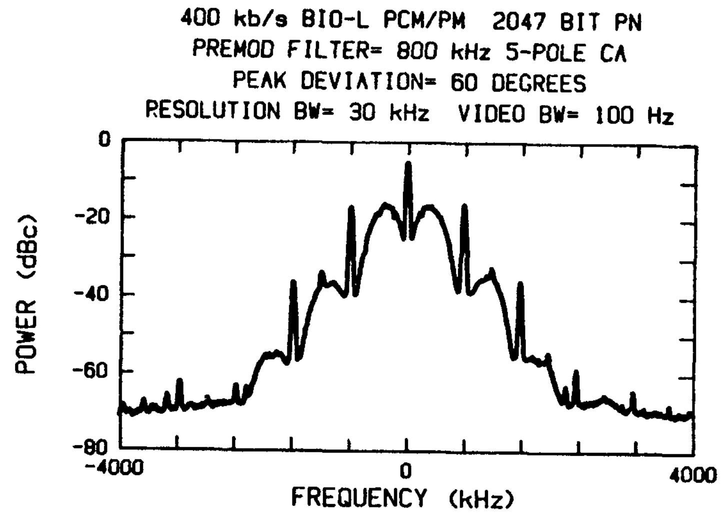


Figure 87. RF Spectrum PREMOD=800 kHz CA Peak DEV=60 Degrees

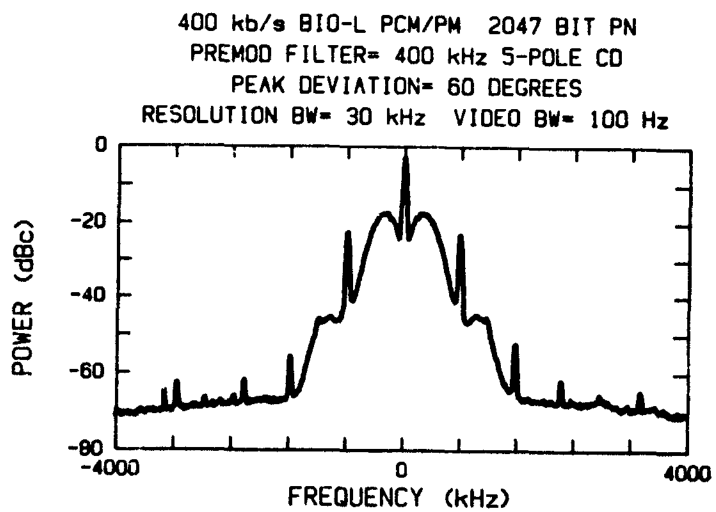


Figure 88. RF Spectrum PREMOD=400 kHz CD Peak DEV=60 Degrees

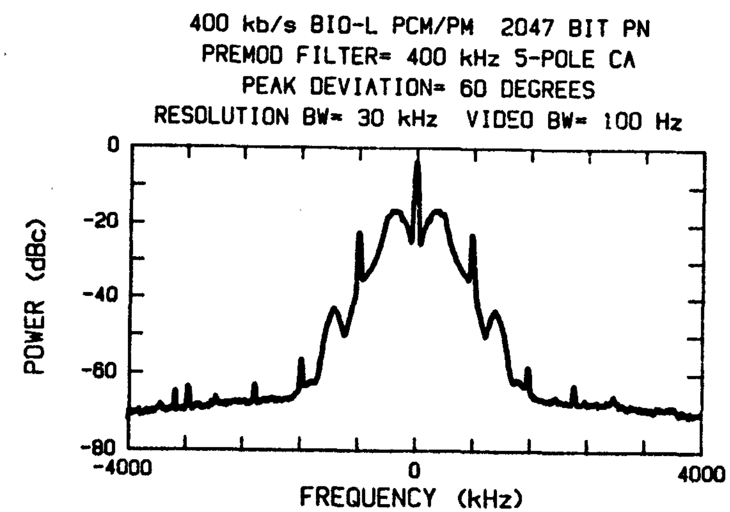


Figure 89. RF Spectrum PREMOD=400 kHz CA Peak DEV=60 Degrees

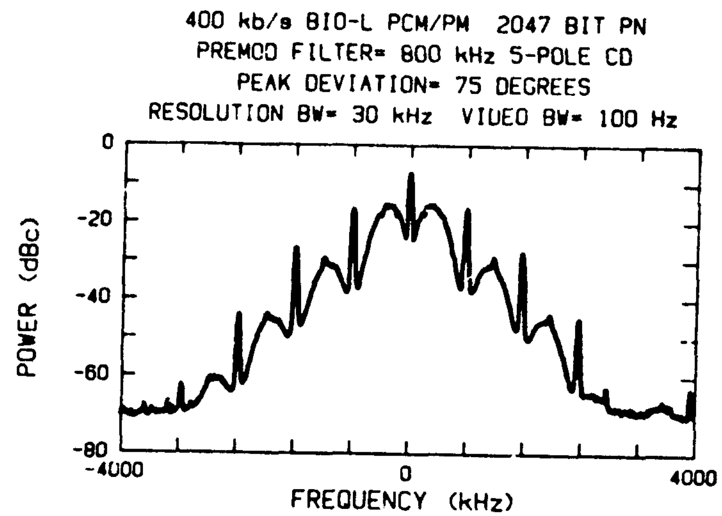


Figure 90. RF Spectrum PREMOD=800 kHz CD Peak DEV=75 Degrees

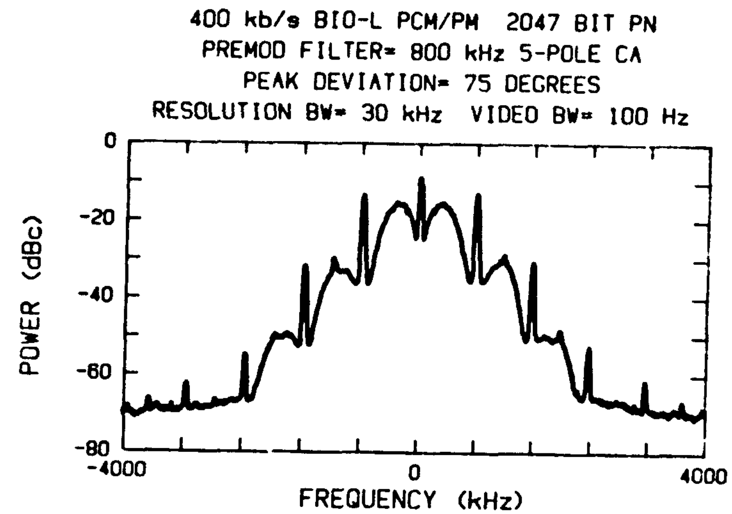


Figure 91. RF Spectrum PREMOD=800 kHz CA Peak DEV=75 Degrees

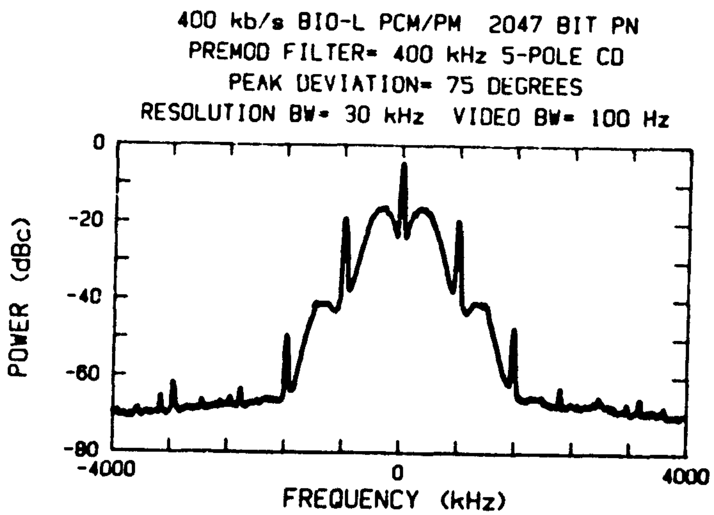


Figure 92. RF Spectrum PREMOD=400 kHz CD Peak DEV=75 Degrees

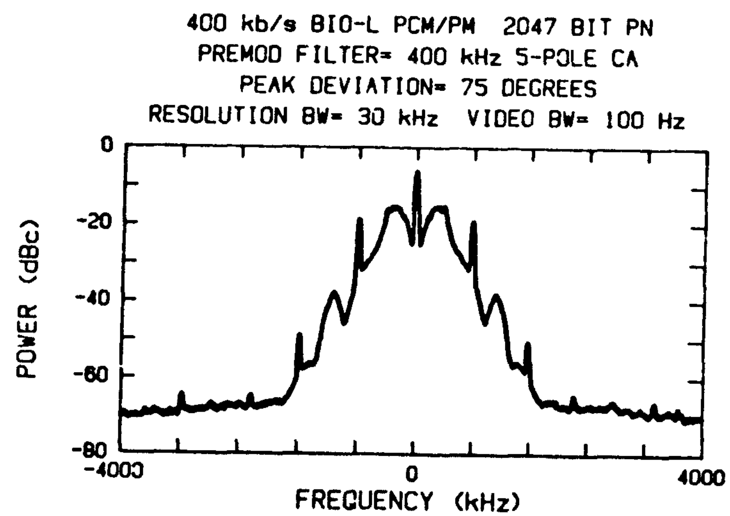


Figure 93. RF Spectrum PREMOD=400 kHz CA Peak DEV=75 Degrees

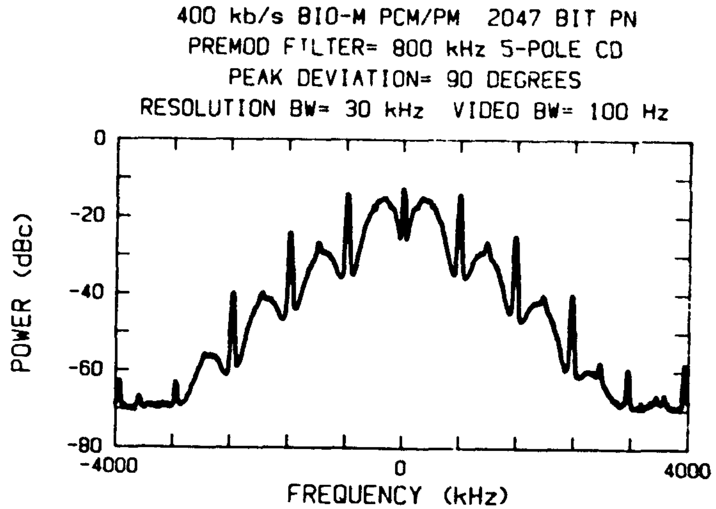


Figure 94. RF Spectrum PREMOD=800 kHz CD Peak DEV=90 Degrees

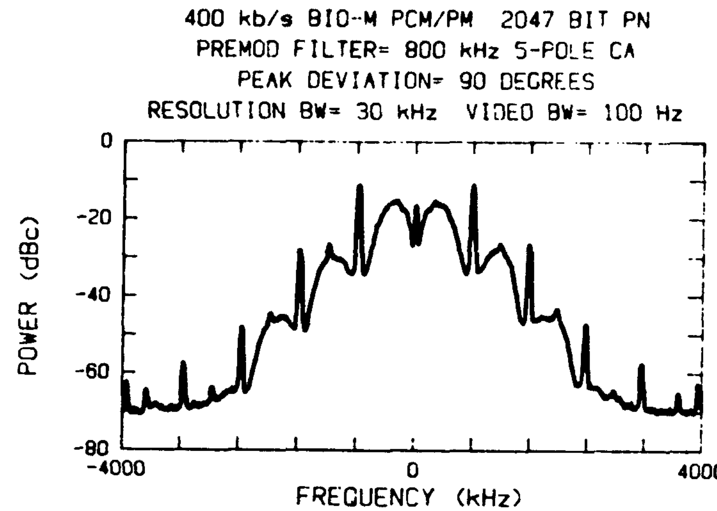


Figure 95. RF Spectrum PREMOD=800 kHz CA Peak DEV=90 Degrees

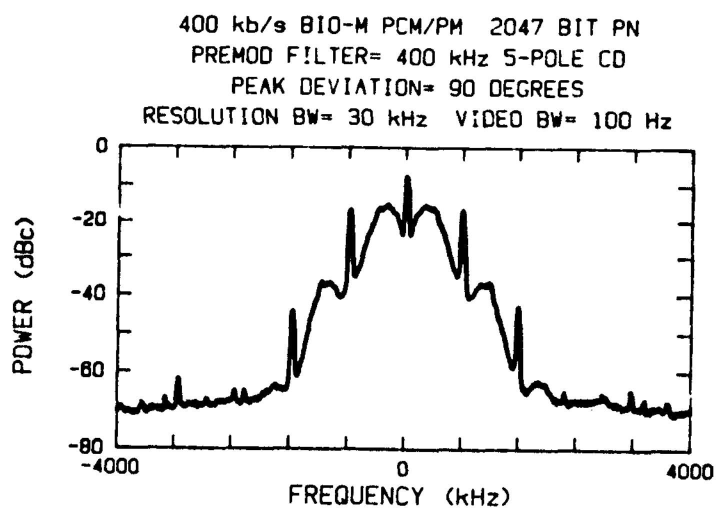


Figure 96. RF Spectrum PREMOD=400 kHz CD Peak DEV=90 Degrees

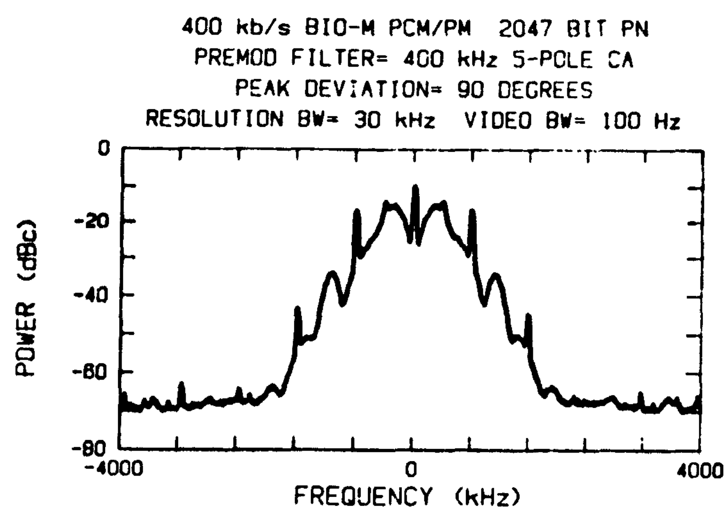


Figure 97. RF Spectrum PREMOD=400 kHz CA Peak DEV=90 Degrees

PHASE SHIFT KEYING

Phase shift keying (PSK) is a method for transmitting digital data in which the carrier is multiplied by +1 if one state of a binary digital signal is to be transmitted, and -1 if the other state is to be transmitted. This produces two signals which are exact opposites of each other (antipodal). The multiplication is usually accomplished using a double-balanced mixer. The performance of PSK is very similar to the performance of PCM/PM ($\pm 90^{\circ}$). The major differences include:

1. If the signals applied to the double-balanced mixer are properly adjusted, the spectral spikes can be minimized or eliminated entirely. Therefore, the occupied bandwidth of a PSK signal may be narrower than the occupied bandwidth of a PCM/PM ($\pm 90^{\circ}$) signal.

2. A PSK signal where the modulating signal has been filtered does not have a constant amplitude (see figure 98). If the PSK signal is limited, the occupied bandwidth increases significantly. Therefore, if the carrier is amplitude-modulated before the final amplifier stage, the final amplifier must be operated in the linear region. This reduces gain and efficiency. The other option for spectral control is to use a bandpass filter after the final amplification. Small, low loss, stable, narrow band, inexpensive filters are difficult to build at 2 GHz.

3. The insertion loss of double-balanced mixers is typically 6 to 7 dB. This means that the signal must be amplified more to make up for this loss.

4. The modulator for PSK is simpler than the modulator for PCM/PM.

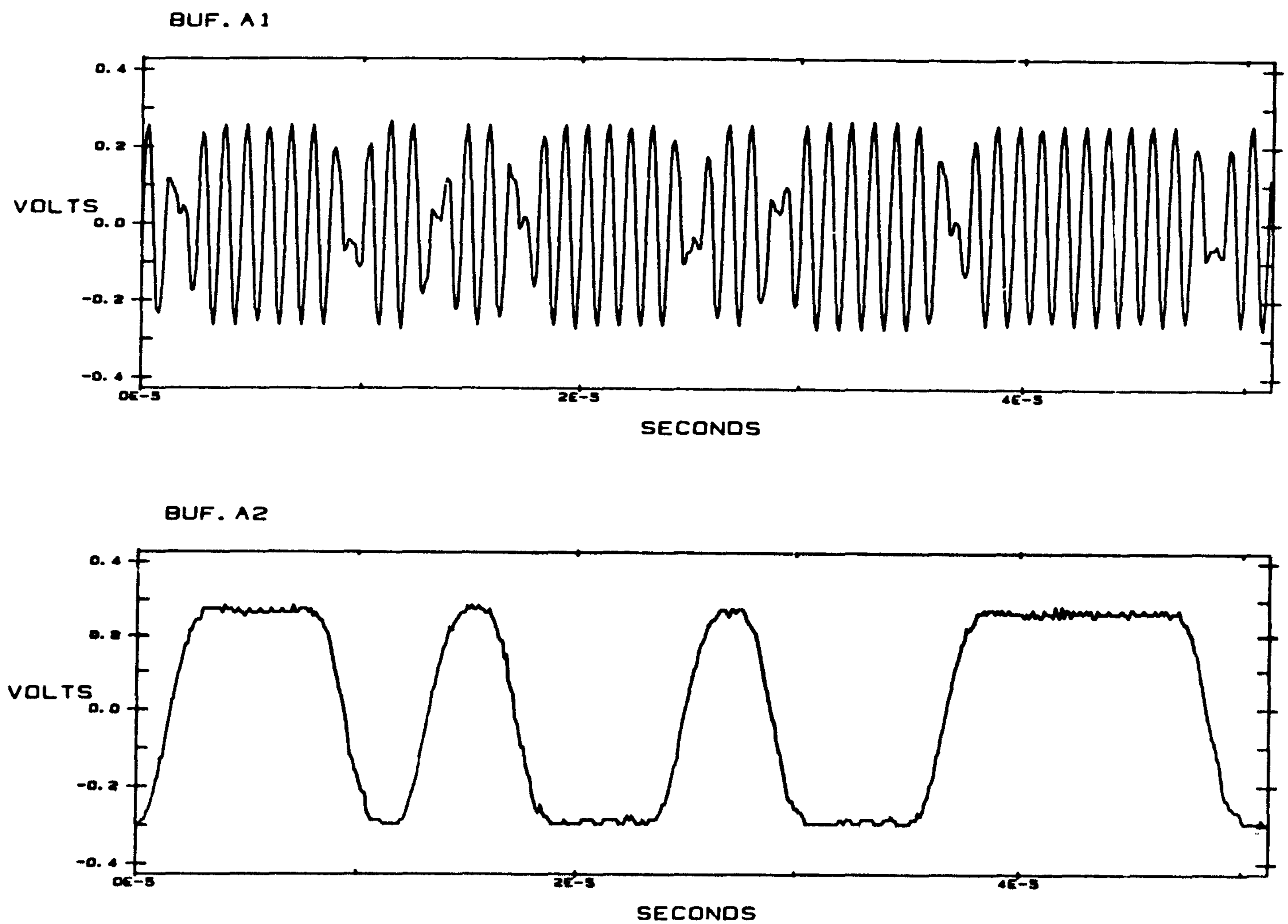


Figure 98. PSK Waveform (Upper Trace) and PCM Signcl.

HYBRID SYSTEMS

Hybrid systems are defined as systems in which more than one type of signal must be multiplexed together on the same transmitter. An example of this is multiplexing subcarrier oscillators (SCOs) with a PCM signal on the same FM transmitter. There are two ways of doing this:

1. The PCM signal can be put on the baseband with the SCOs at a higher frequency.

2. The SCOs can be at lower frequencies and the PCM signal can modulate another SCO.

An example of the first type of system would be a 256-kb/s randomized NRZ-L bit stream that needs to be transmitted along with two analog signals with 2 kHz of required bandwidth each. The baseband spectrum of such a system is shown in figure 99. The SCO frequencies ($\pm$8 kHz deviation) were chosen to be near the spectral null of the NRZ-L PCM signal. The RF spectrum of this system is shown in figure 100. The occupied bandwidth is approximately 1.5 MHz. Therefore, this signal will fit in an IRIG narrow band (1 MHz) channel.

The BER versus IF SNR in a 256-kHz bandwidth is shown in figure 101 for four IF bandwidths. It is interesting to note that the best PCM data quality is achieved with a 300-kHz IF bandwidth. This filter essentially rejects the two SCOs. The BER performance with all four filters is essentially what one would expect without the SCOs. This suggests that with this type of transmitted signal, one should use two receivers. A receiver with an IF bandwidth approximately equal to the bit rate to recover the PCM signal, and a receiver with a wider IF bandwidth to recover the SCO data. The output of the wider bandwidth receiver should also be predetection-recorded to increase the probability of getting the best possible data quality. The SNR at the output of a 288-kHz discriminator with a 2-kHz linear phase output filter at a 34-dB IF SNR (1 MHz IF bandwidth) was 48 dB (full-scale sine wave rms/noise rms). The SNR was 35 dB at a 12.5-dB IF SNR. The SNRs at the output of a 256-kHz discriminator were 55 dB and 35 dB at IF SNRs of 34 dB and 12.5 dB, respectively. For comparison purposes, the IF SNR in a 256-kHz bandwidth required to achieve a 10^{-5} BER with the 256-kb/s PCM signal modulating a 450-kHz SCO is approximately 19 dB (1.5 MHz IF bandwidth). The occupied bandwidth would be approximately 3.5 MHz.

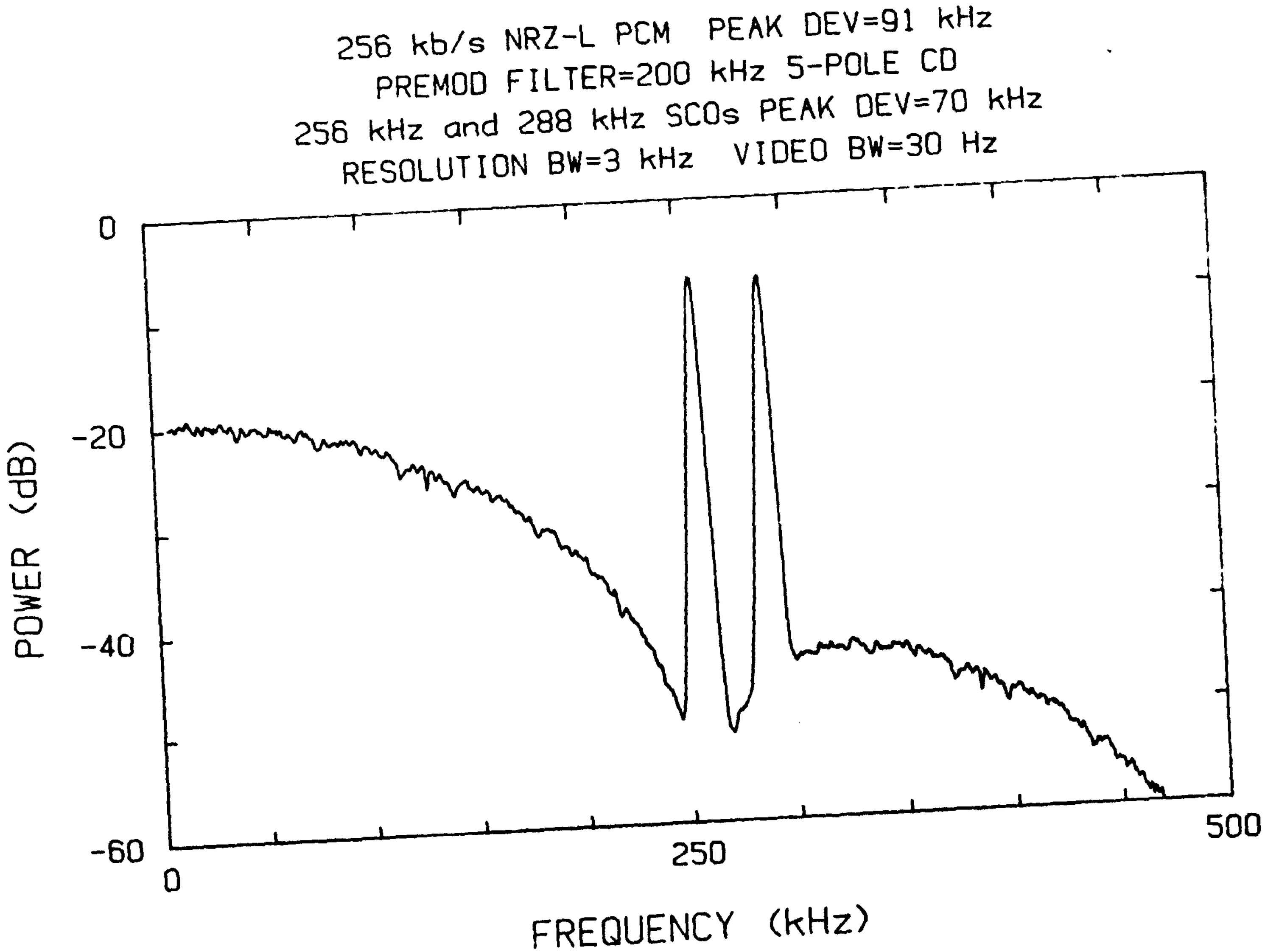


Figure 99. Baseband Spectrum 256 kb/s NRZ with 2 SCOs.

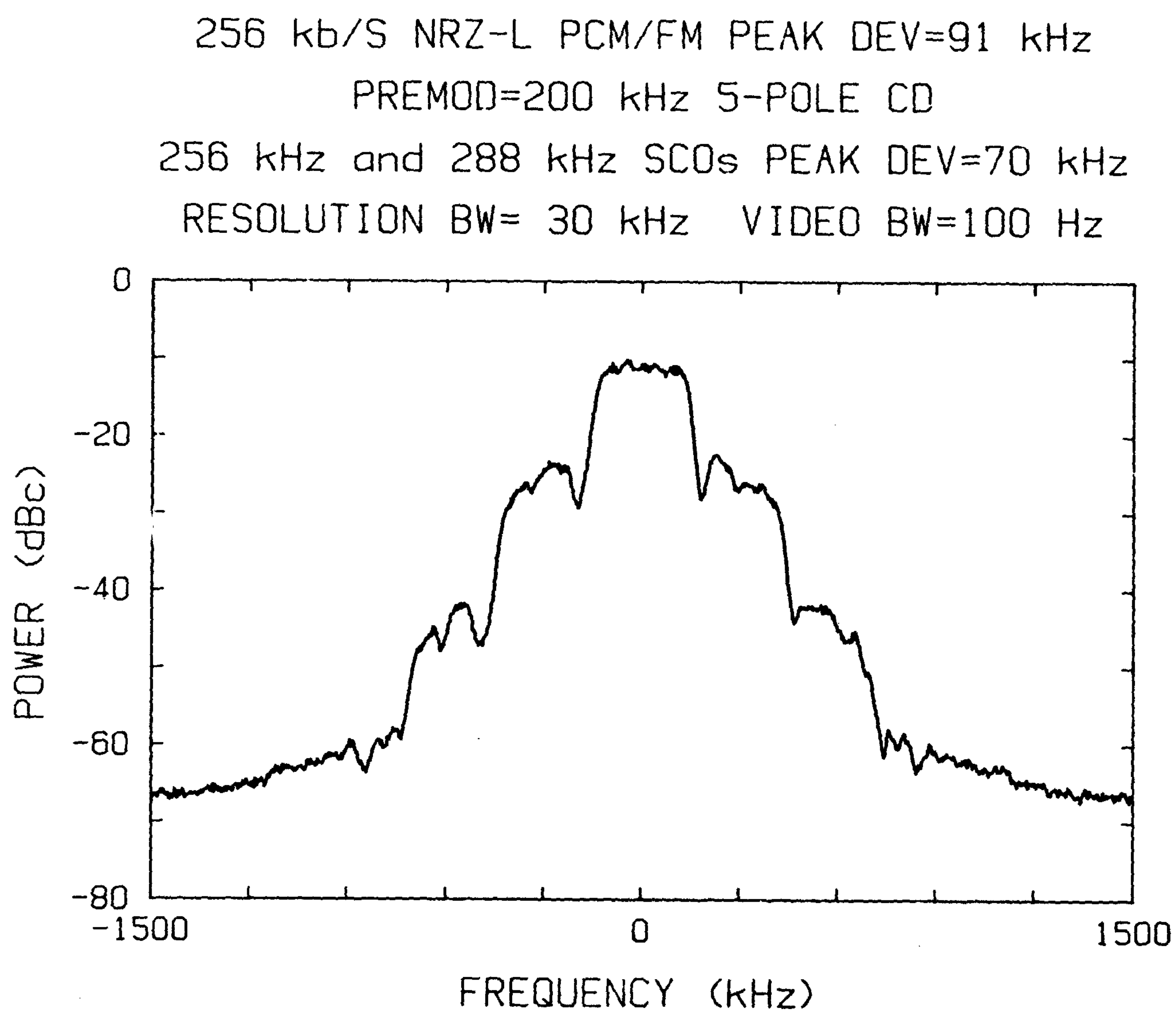


Figure 100. RF Spectrum 256 kb/s PCM/FM NRZ with 2 SCOs.

MODULATION TYPE	BIT RATE kb/s	IF BW kHz	PREMOD kHz	PREMOD TYPE	PEAK DEV	BIT DET
O NRZ-L PCM/FM	256	1500	200	CD	90	F/S
+ NRZ-L PCM/FM	256	1000	200	CD	90	F/S
o NRZ-L PCM/FM	256	500	200	CD	90	F/S
* NRZ-L PCM/FM	256	300	200	CD	90	F/S

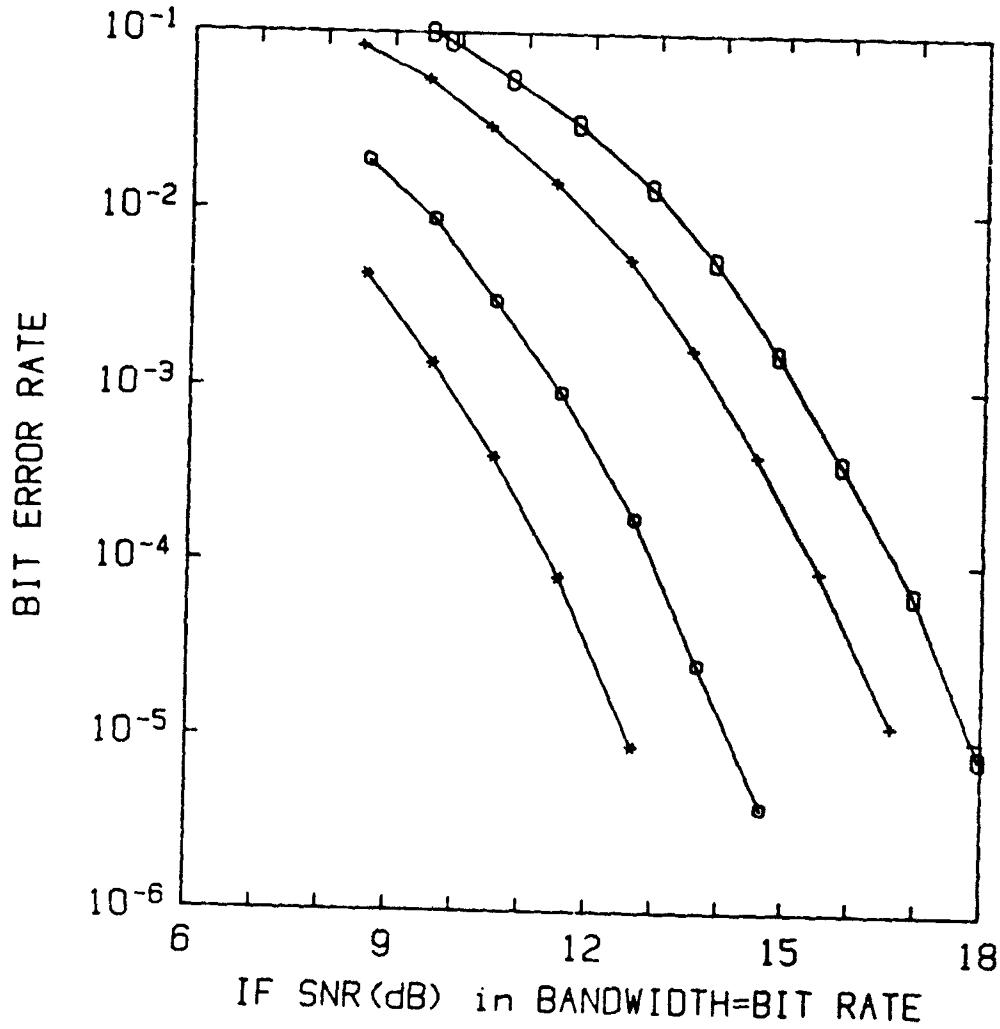


Figure 101. BER Versus IF BW for 256 kb/s NRZ with 2 SCOs.

PREDETECTION RECORDING

Introduction

There are several methods for recording PCM telemetry signals. These methods are illustrated in figure 102. This report will only discuss predetection recording. Refer to references 1 and 8 for discussions of the other methods illustrated in figure 102. The test setup for the predetection tests is shown in figure 103. Tests were performed both with and without a tape recorder/reproducer and with demodulation at the tape carrier frequency and after upconversion to a higher frequency (typically 10 or 20 MHz).

Test Results

Tests were conducted using both PCM/FM and PCM/PM and a variety of bit rates, receiver IF bandwidths, and predetection carrier frequencies. Figure 104 shows that the BER performance of 300 kb/s NRZ-L PCM/FM is the same with either a 450-kHz or a 900-kHz predetection carrier frequency. The BER performance of the predetection signals with 500 kHz receiver and playback IF bandwidths was approximately 1 dB better than the BER performance of direct receiver video with a 500-kHz IF bandwidth. The reason for this is that putting two 500-kHz bandwidth filters in series results in a filter with a bandwidth of approximately 400 kHz. This increases the actual IF SNR by 1 dB and therefore improves the BER by approximately 1 dB. An entry of 0 in the legend for the figures in this section means that that part of the test setup was not used for this data; e.g., no recorder was used for the data in figure 104. The data presented in figures 105 and 106 show the effects of receiver IF bandwidth and tape recording on BER performance. The degradation due to widening the receiver IF bandwidth at a 10^{-4} BER was approximately 0.5, 1.1, and 2.3 dB for the 1.5-, 2.4-, and 4.0-MHz bandwidths, respectively. The recorder/reproducer caused a degradation of no more than 0.3 dB. Figure 107 shows the effect of varying the receiver IF bandwidth at a bit rate of 900 kb/s and a predetection frequency of 900 kHz. The BERs with the 1000- and 1500-kHz bandwidths were very similar, while the 2400-kHz bandwidth caused approximately 0.5 dB of degradation and the 4000-kHz bandwidth caused approximately 1.8 dB of degradation at a BER of 10^{-4}. The degradation with the 4000-kHz IF bandwidth is mostly caused by

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[1] Secretariat, Range Commanders Council. Telemetry Standards. White Sands Missile Range, New Mexico, RCC, Sep 1980. (IRIG Standard 106-80).

[8] Law, E. L. Serial High Density Digital Recording Using a Wideband Analog IRIG Recorder/Reproducer. Pacific Missile Test Center, Point Mugu, California, May 1981. (TP-81-20).

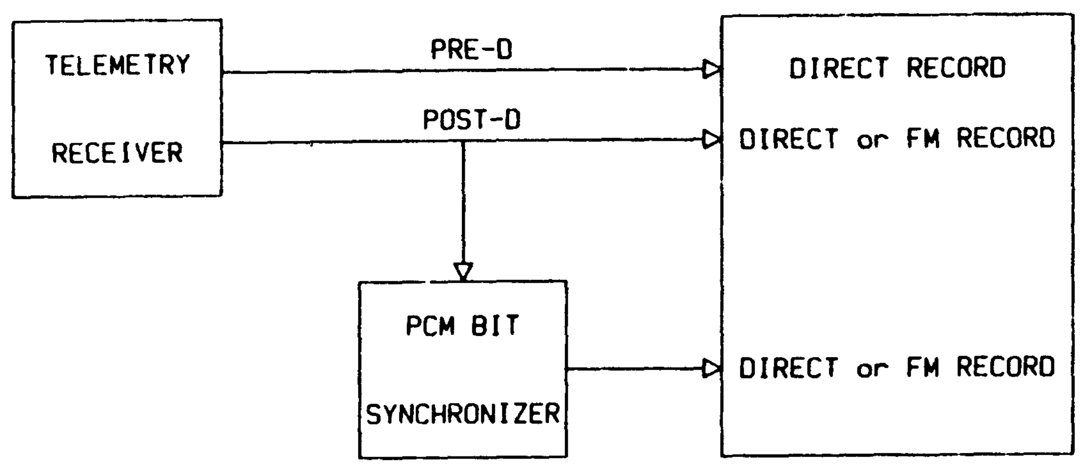

Figure 102. Methods for Recording PCM Telemetry Signals.

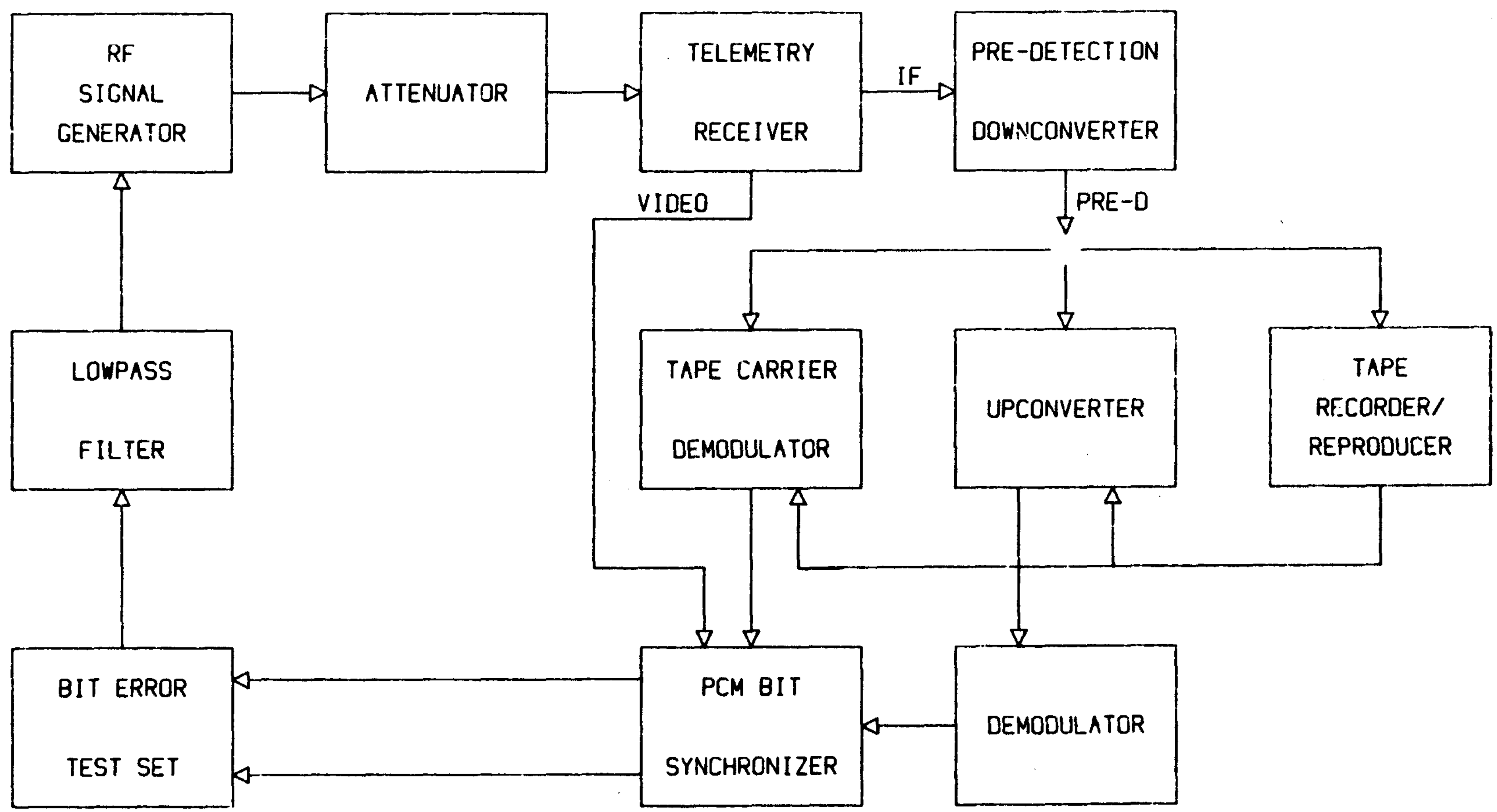

Figure 103. Predetection Test Setup.

MOD TYPE	BIT RATE kb/s	IFBW kHz	PBK kHz	PRED kHz	VID kHz	PEAK DEV	RCD IPS
0 NRZ-L PCM/FM	300	1000	0	0	250	107	0
+ NRZ-L PCM/FM	300	500	0	0	250	107	0
o NRZ-L PCM/FM	300	500	500	450	250	107	0
* NRZ-L PCM/FM	300	500	500	900	250	107	0

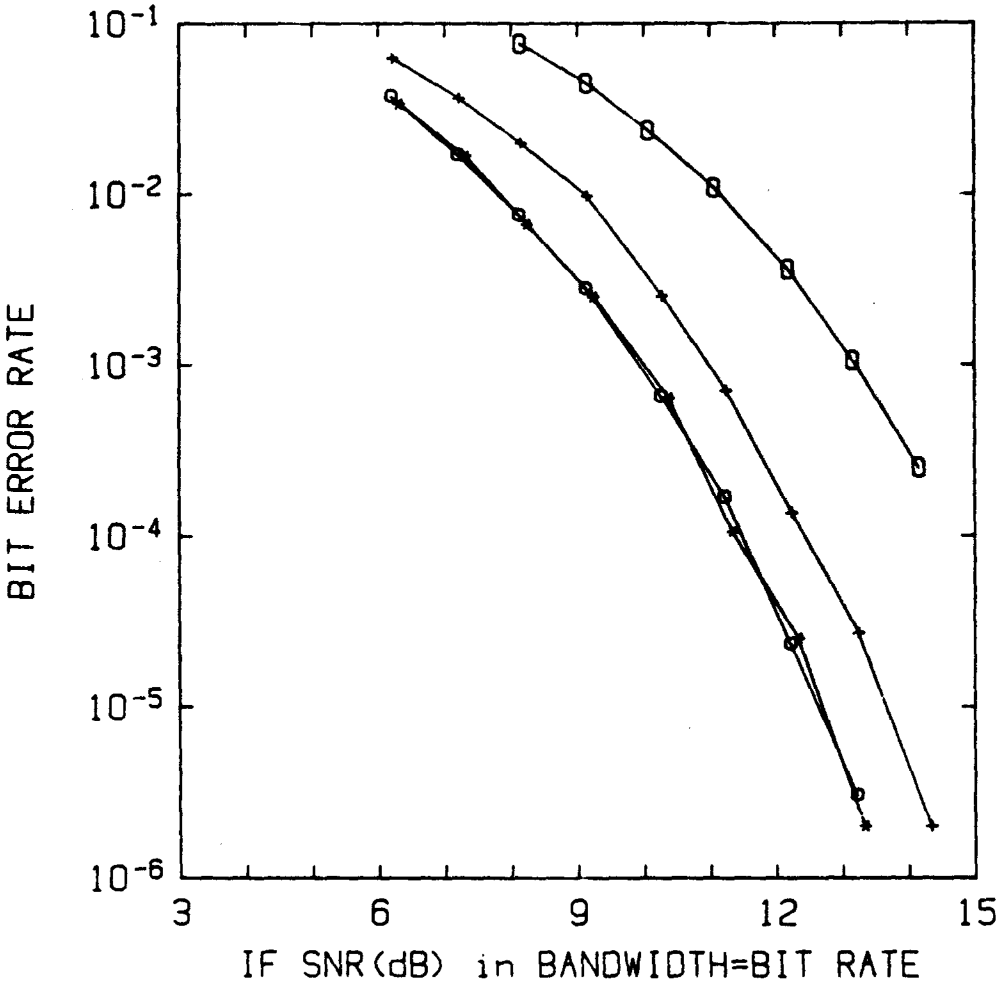

Figure 104. BER with 500 kHz IF BW 300 kb/s and 450 and 900 PRE-D.

MOD TYPE	BIT RATE kb/s	IFBW kHz	PBK kHz	PRED kHz	VID kHz	PEAK DEV	RCD IPS
0 NRZ-L PCM/FM	600	1500	1000	900	500	214	120
+ NRZ-L PCM/FM	600	1500	1000	900	500	214	0
o NRZ-L PCM/FM	600	1000	1000	900	500	214	120
* NRZ-L PCM/FM	600	1000	1000	900	500	214	0

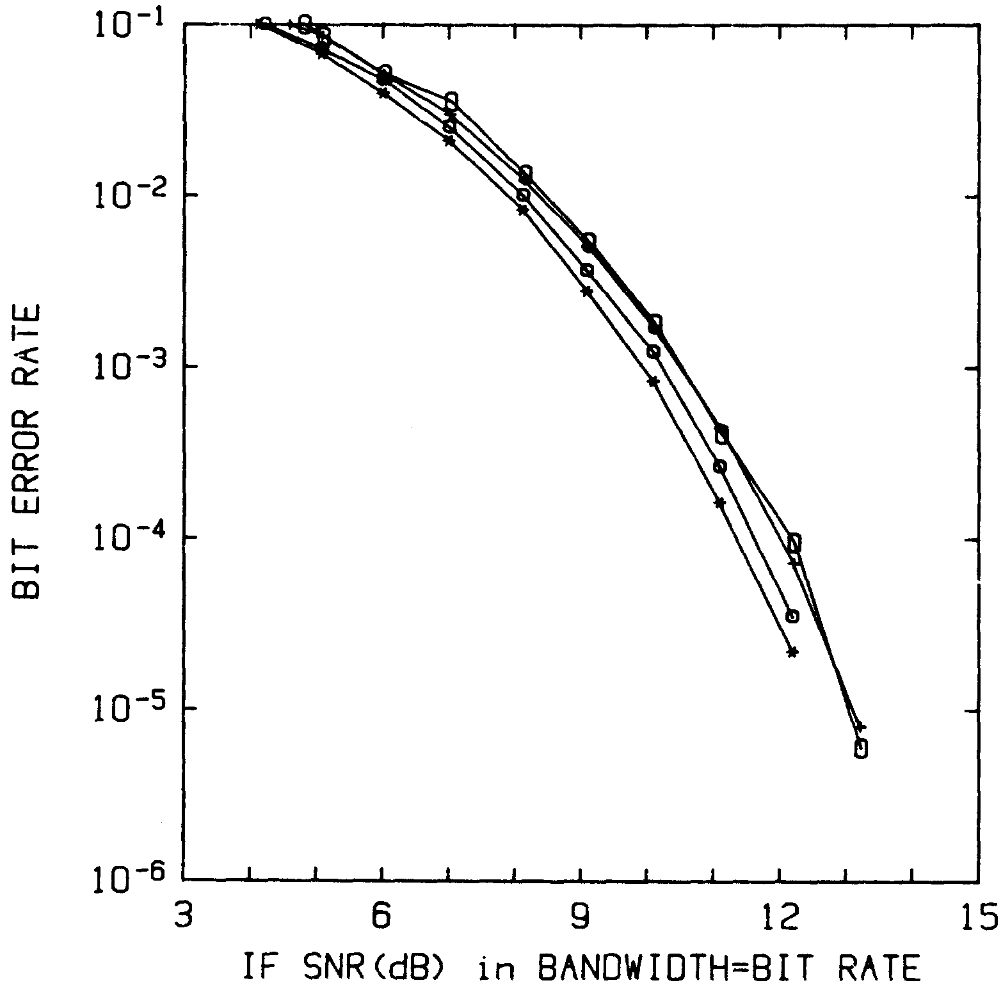

Figure 105. BER with and without Recording.

MOD TYPE	BIT RATE kb/s	IFBW kHz	PBK kHz	PRED kHz	VID kHz	PEAK DEV	RCD IPS
X NRZ-L PCM/FM	600	4000	1000	900	500	214	120
0 NRZ-L PCM/FM	600	4000	1000	900	500	214	0
+ NRZ-L PCM/FM	600	2400	1000	900	500	214	120
o NRZ-L PCM/FM	600	2400	1000	900	500	214	0
* NRZ-L PCM/FM	600	1000	1000	900	500	214	0

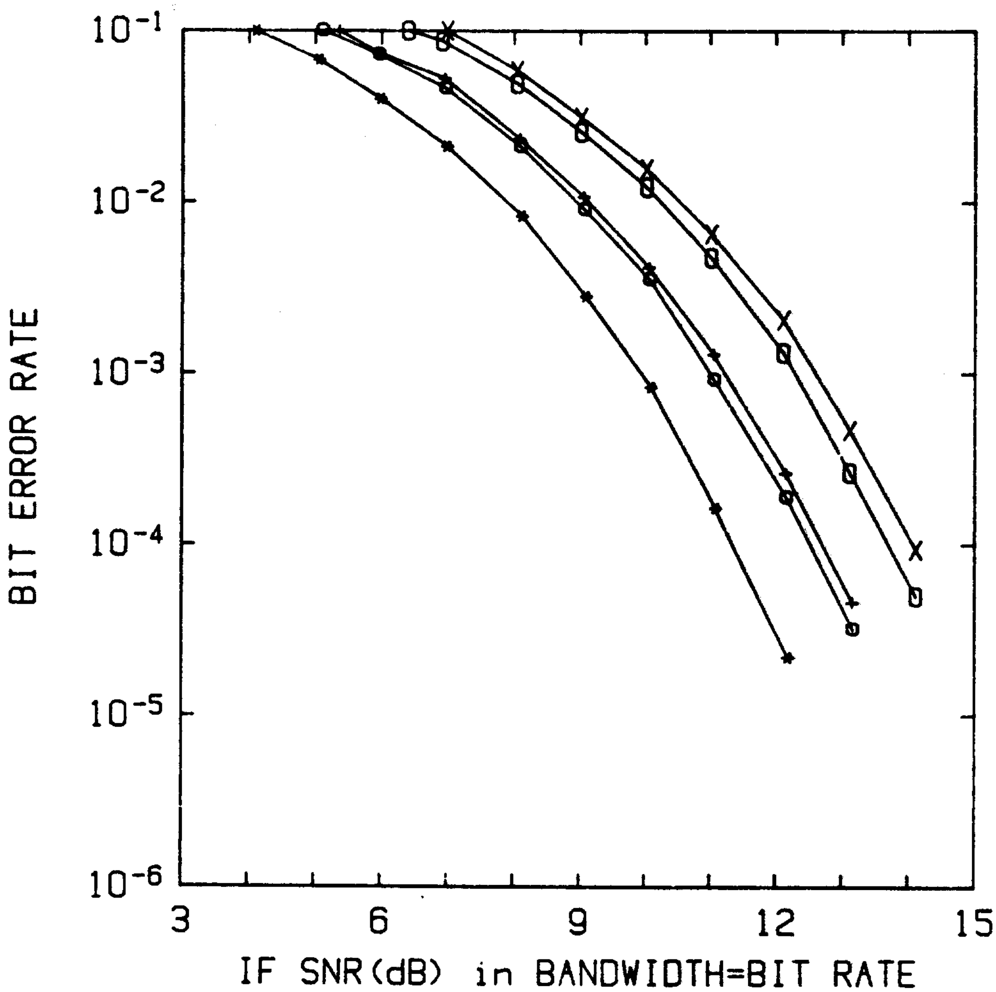

Figure 106. BER with and without Recording (Wide IF BW).

MOD TYPE	BIT RATE kb/s	IFBW kHz	PBK kHz	PRED kHz	VID kHz	PEAK DEV	RCD IPS
0 NRZ-L PCM/FM	900	4000	1000	900	1000	321	0
+ NRZ-L PCM/FM	900	2400	1000	900	1000	321	0
o NRZ-L PCM/FM	900	1500	1000	900	1000	321	0
* NRZ-L PCM/FM	900	1000	1000	900	1000	321	0

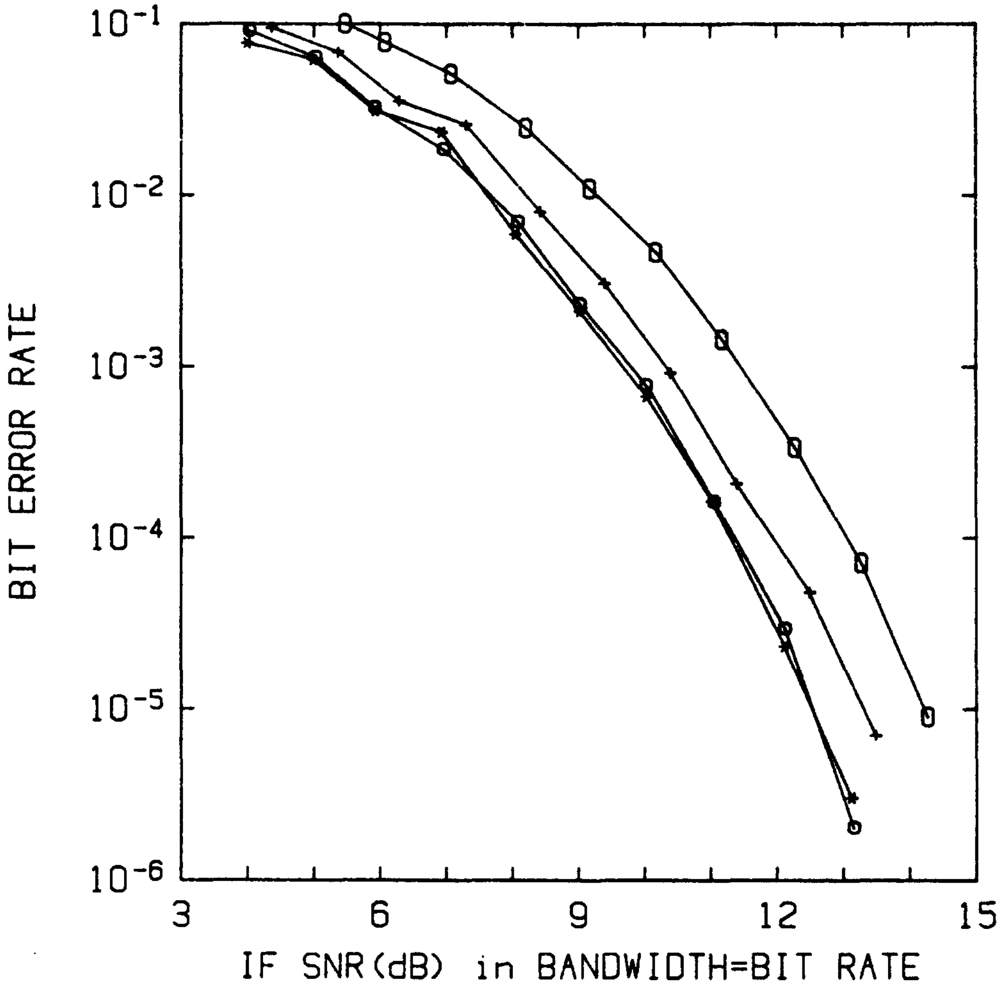

Figure 107. BER for 900 PRE-D and IF BW=1, 1.5, 2.4 and 4 MHz.

noise folding back across zero hertz and increasing the noise power in the playback demodulator's passband. This is illustrated in figure 108. The higher amplitude trace in each group is the noise with a 3000-kHz IF bandwidth and the lower amplitude trace is the noise with a 1500-kHz IF bandwidth. The noise power is the same with both filters for frequencies between 9.6 and 10.4 MHz and 900 and 1300 kHz. However, the 3000-kHz IF bandwidth causes the noise power between 500 kHz and 800 kHz to increase by 1 to 2 dB. The predetection downconverter also does some low pass filtering. The unmodulated carrier level was 0 dBc for these plots. Figure 109 shows that using a 900-kHz predetection carrier with 900 kb/s NRZ-L PCM/FM data causes a data degradation of approximately 0.2 dB at a 10^{-4} BER when compared to the BER performance using a 1.8-MHz predetection carrier frequency. This slight degradation may well be preferable to doubling the tape speed so that the 1.8-MHz predetection carrier could be used.

Figure 110 compares the BER performance of upconversion and demodulation (500-kHz playback(PBK)) to demodulation at tape carrier (360-kHz PBK). This data shows that upconversion and demodulation performs a few tenths of a dB better than demodulation at the tape carrier frequency when the bit rate is much less than the tape carrier frequency. The data in figure 111 show that upconversion and demodulation perform approximately 1.6 dB better than demodulation at the tape carrier frequency when the NRZ PCM/FM bit rate is equal to the predetection carrier frequency. Most of the degradation is due to excessive bandpass filtering in the tape carrier discriminator. The bandwidth is only 720 kHz (900 $\pm$40%) which degrades the BER by more than 1 db.

The data in figure 112 show that using a 1200-kHz predetection carrier frequency with 1200 kb/s NRZ-L PCM/FM performs 1 dB better than using a 900-kHz carrier at a 10^{-4} BER with 1500 kHz bandwidths in both the receiver and the playback demodulator. The difference is 1.8 dB when the receiver bandwidth is 2400 kHz. The data in figure 113 show that a 1200-kHz predetection carrier performs 2 to 3 dB better than a 900-kHz carrier for 1200 kb/s NRZ-M PCM/PM ($\pm 90^{\circ}$). Comparing the data in figures 112 and 113, one discovers that PCM/FM requires less IF SNR than PCM/PM under these conditions.

Figure 114 presents data for biphase level PCM/PM ($\pm 75^{\circ}$) for demodulation at 900 kHz and at 10 MHz (PRED = 0). Demodulation at 900 kHz degrades the 300-kb/s performance by 0.3 dB and the 600-kb/s performance by 1 dB at a 10^{-4} BER. The difference in BER performance at a 10^{-4} BER between 300 kb/s and 450 kb/s is approximately 0.5 dB, while the difference between 300 kb/s and 600 kb/s is approximately 1.8 dB. This suggests that the highest recommended biphase bit rate should be one-half of the predetection frequency.

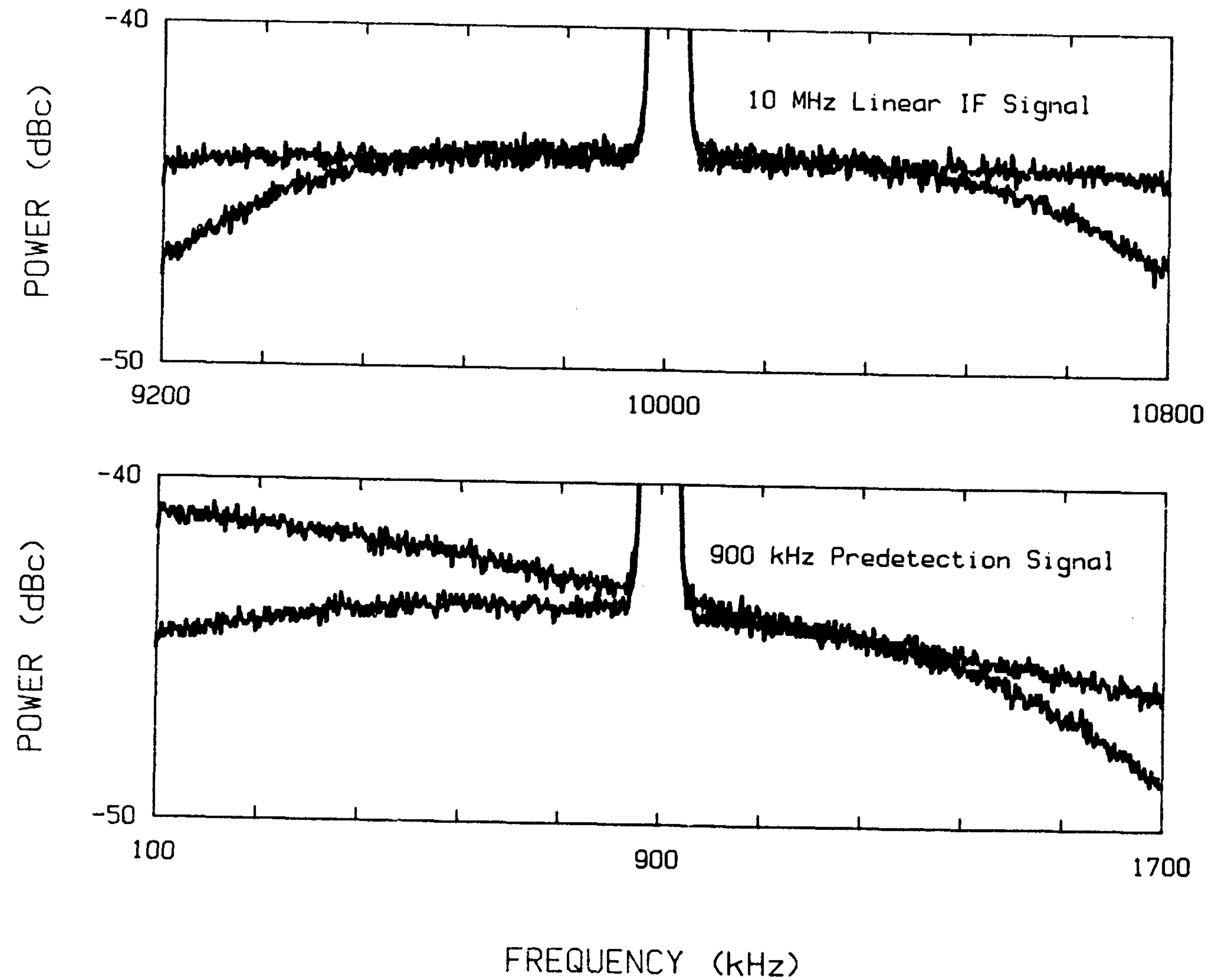

Figure 108. Noise PSDs for IF and PRE-D Signals.

MOD TYPE	BIT RATE kb/s	IFBW kHz	PBK kHz	PRED kHz	VID kHz	PEAK DEV	RCD IPS
o NRZ-L PCM/FM	900	1500	1000	1800	1000	321	0
* NRZ-L PCM/FM	900	1500	1000	900	1000	321	0

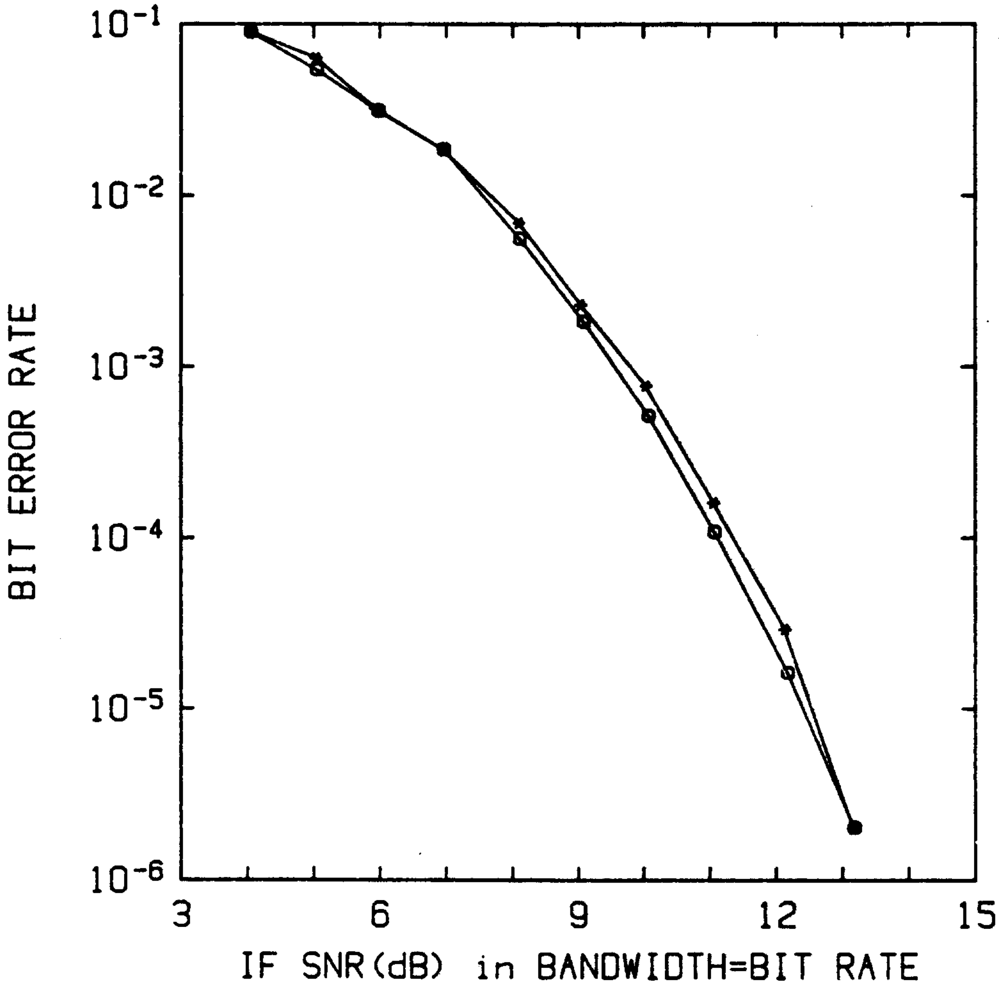

Figure 109. BER for 900 kb/s NRZ 900 and 1800 kHz PRE-D.

MOD TYPE	BIT RATE kb/s	IFBW kHz	PBK kHz	PRED kHz	VID kHz	PEAK DEV	RCD IPS
X NRZ-L PCM/FM	300	1000	360	900	300	107	120
O NRZ-L PCM/FM	300	1000	360	900	300	107	0
+ NRZ-L PCM/FM	300	1000	500	900	250	107	120
o NRZ-L PCM/FM	300	1000	500	900	250	107	0
* NRZ-L PCM/FM	300	500	500	450	250	107	0

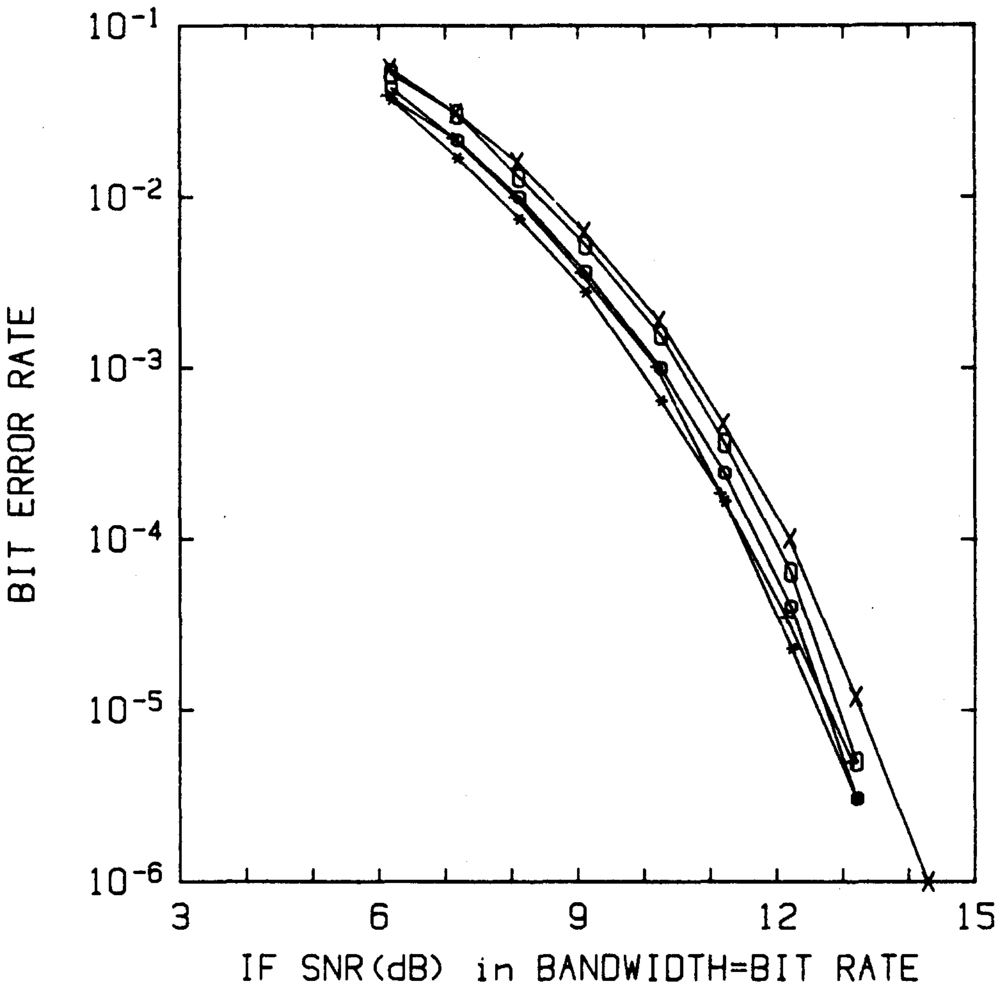

Figure 110. BER for Tape Carrier and Upconversion (300 kb/s).

	MOD TYPE	BIT RATE kb/s	IFBW kHz	PBK kHz	PRED kHz	VID kHz	PEAK DEV	RCD IPS
□	NRZ-L PCM/FM	900	2400	720	900	600	321	0
+	NRZ-L PCM/FM	900	2400	1000	900	1000	321	0
o	NRZ-L PCM/FM	900	1500	720	900	600	321	0
*	NRZ-L PCM/FM	900	1500	1000	900	1000	321	0

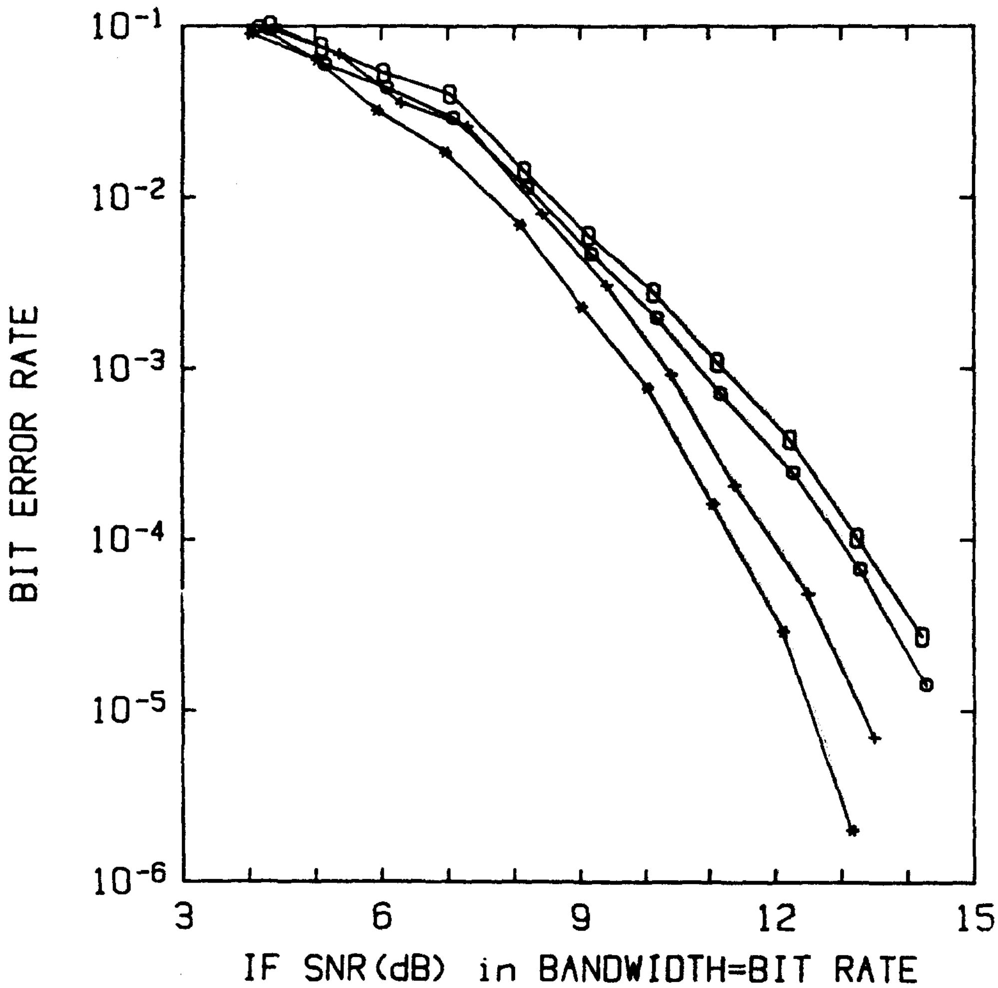

Figure 111. BER for Tape Carrier and Upconversion (900 kb/s).

MOD TYPE	BIT RATE kb/s	IFBW kHz	PBK kHz	PRED kHz	VID kHz	PEAK DEV	RCD IPS
X NRZ-L PCM/FM	1200	2400	1500	900	1000	420	0
O NRZ-L PCM/FM	1200	1500	1500	900	1000	420	0
+ NRZ-L PCM/FM	1200	2400	1500	1200	1000	420	0
o NRZ-L PCM/FM	1200	1500	1500	1200	1000	420	0
* NRZ-L PCM/FM	1200	1500	0	0	1000	420	0

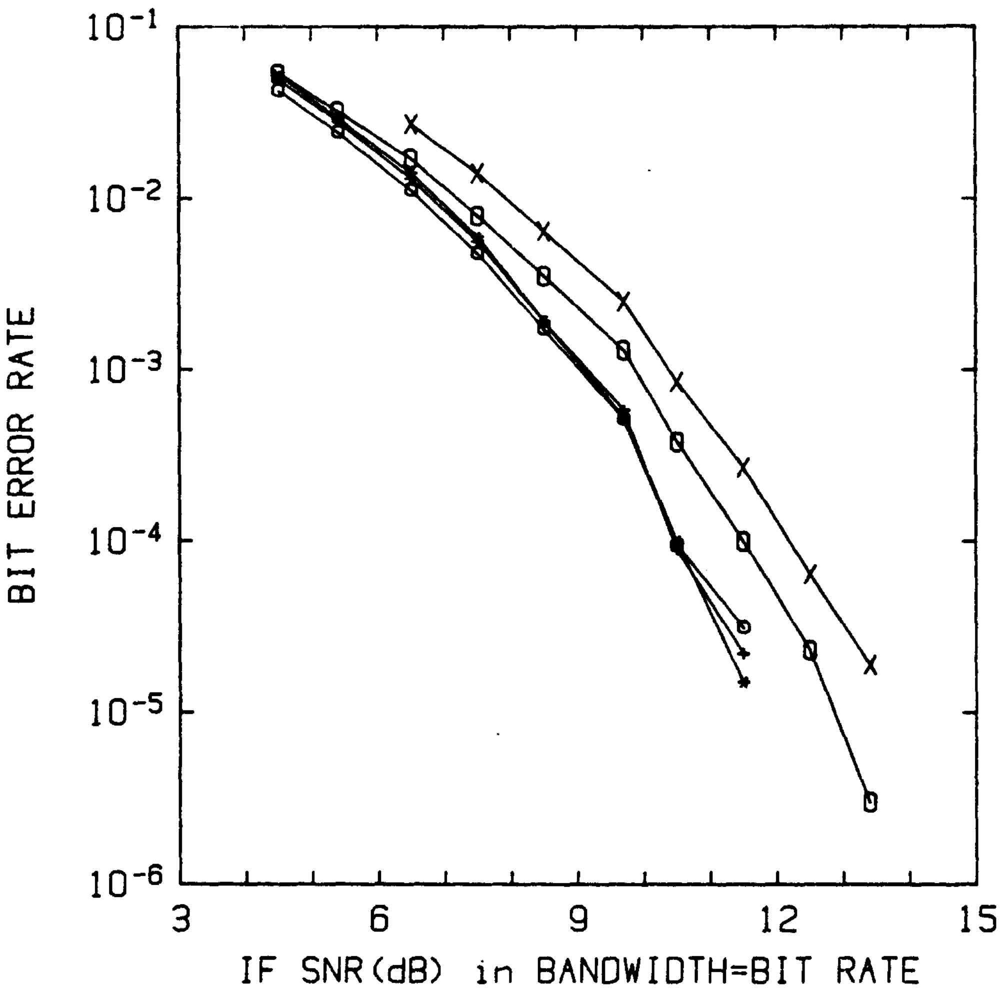

Figure 112. BER for 900 and 1200 kHz PRE-D 1200 kb/s PCM/FM.

	MOD TYPE	BIT RATE kb/s	IFBW kHz	PBK kHz	PRED kHz	VID kHz	PEAK DEV	RCD IPS
0	NRZ-M PCM/PM	1200	1500	2400	900	1000	90	0
+	NRZ-M PCM/PM	1200	2400	1500	900	1000	90	0
o	NRZ-M PCM/PM	1200	2400	2400	900	1000	90	0
*	NRZ-M PCM/PM	1200	2400	2400	1200	1000	90	0

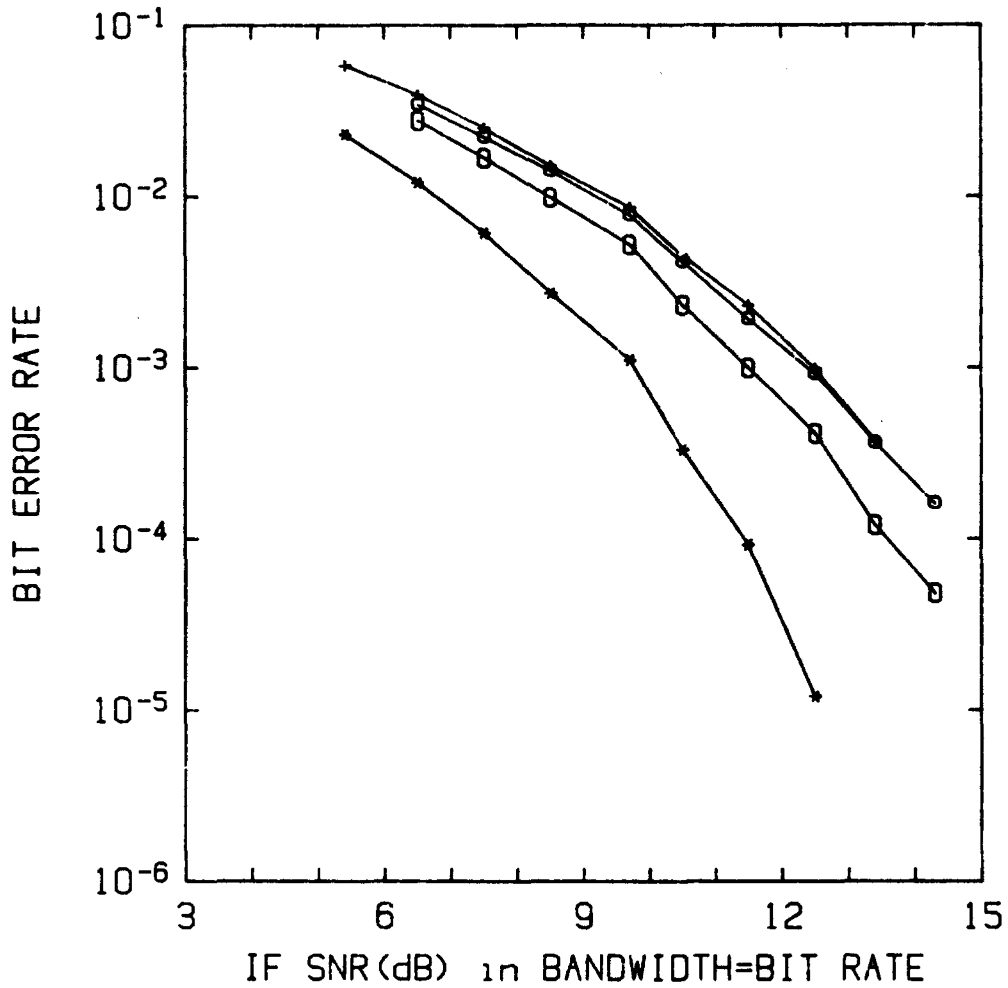

Figure 113. BER for 900 and 1200 kHz PRE-D 1200 kb/s PCM/PM.

MOD TYPE	BIT RATE kb/s	IFBW kHz	PBK kHz	PRED kHz	VID kHz	PEAK DEV	RCD IPS
0 BIO-L PCM/PM	600	1500	2000	0	2000	75	0
X BIO-L PCM/PM	600	1500	2000	900	2000	75	0
+ BIO-L PCM/PM	450	1500	2000	900	2000	75	0
o BIO-L PCM/PM	300	1500	2000	900	2000	75	0
* BIO-L PCM/PM	300	1500	2000	0	2000	75	0

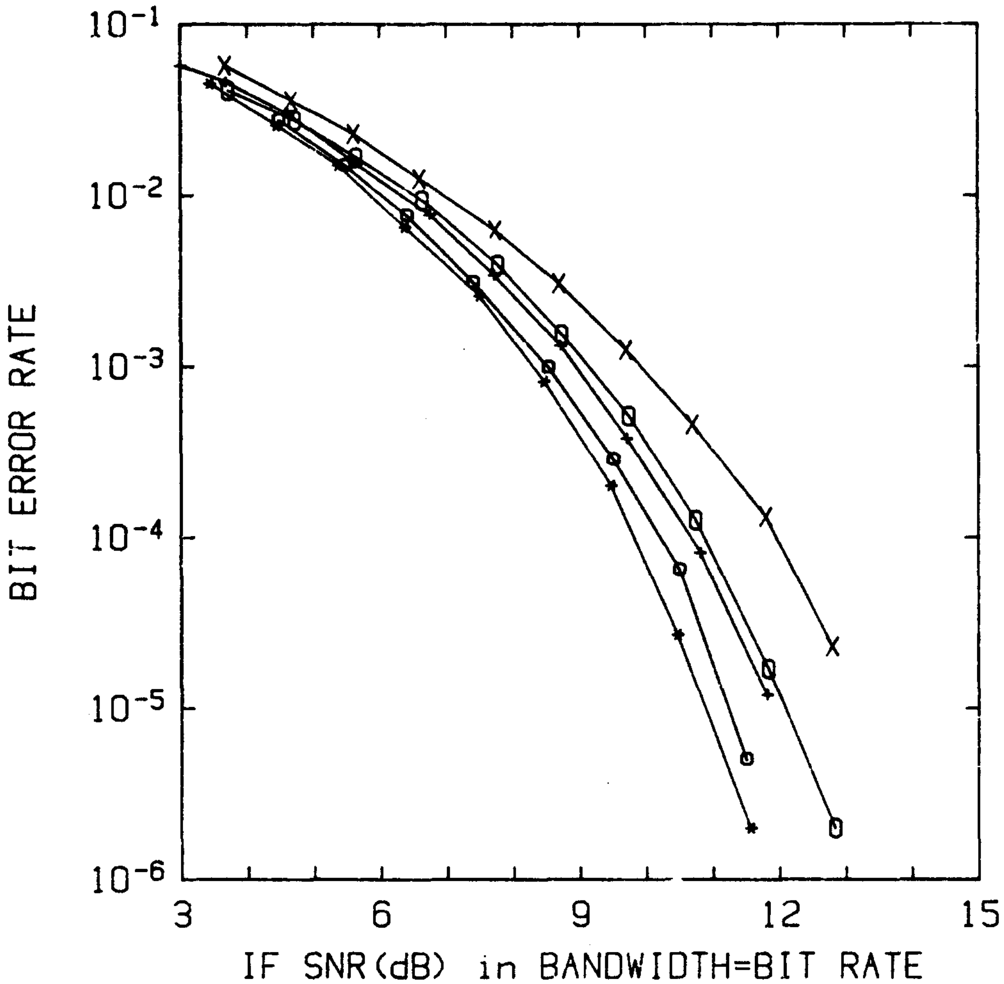

Figure 114. BER for 300, 450 and 600 kb/s Biphase PCM/PM.

CONCLUSIONS

All of these conclusions are based on the assumptions of classical low pass premodulation filters and typical telemetry receivers, demodulators, and PCM bit synchronizers.

1. If wide bandwidths are available, the modulation method which yields the best data quality is NRZ-M PCM/PM ($\pm 90^{\circ}$). The wideband performance of NRZ-M PCM/PM ($\pm 90^{\circ}$) is approximately 1 dB better than optimum NRZ-L PCM/FM at BERs of 10^{-4} to 10^{-5}. The BER performance of the various modulation methods is illustrated in figure 115 and table 9.

2. If the bandwidth is fairly narrow (low pass equivalent of 0.7 times bit rate or less), the modulation method which yields the best data quality is NRZ-L PCM/FM.

3. Biphase level PCM/FM requires approximately 3 dB more IF SNR (measured in a bandwidth equal to the bit rate) to achieve the same BER as NRZ-L PCM/FM.

4. The performance of PCM/PM degrades rather rapidly as the PCM bit stream is filtered. The performance of PCM/FM degrades slowly until the filters are quite narrow.

5. Biphase level PCM/PM ($\pm 75^{\circ}$) performs better than biphase mark PCM/PM ($\pm 90^{\circ}$) at high BERs and performs as well as biphase mark PCM/PM ($\pm 90^{\circ}$) at low BERs when wideband filters are used. Wideband biphase level PCM/PM ($\pm 75^{\circ}$) performs approximately 3.5 dB better than optimum biphase level PCM/FM.

6. The best premodulation filter is the widest filter which allows the RF spectral occupancy requirements to be met.

7. The optimum peak deviations are:

NRZ PCM/FM	0.35 times bit rate.
BIPHASE PCM/FM	0.65 times bit rate.
NRZ PCM/PM	90 to 100 degrees.
BIPHASE PCM/PM	75 to 85 degrees (PM demodulator).
BIPHASE PCM/PM	90 to 100 degrees (PSK demodulator).

MODULATION TYPE	BIT RATE kb/s	IF BW kHz	PREMOD kHz	TYPE	PEAK DEV	BIT DET
X BIO-L PCM/PM	500	4000	1000	CD	60	
O BIO-L PCM/PM	500	4000	1000	CD	75	
+ BIO-M PCM/PM	500	4000	1000	CD	90	
x BIO-L PCM/FM	500	1000	1000	CD	312	
o NRZ-M PCM/PM	500	3000	500	CD	90	I/D
* NRZ-L PCM/FM	500	500	500	CD	178	F/S

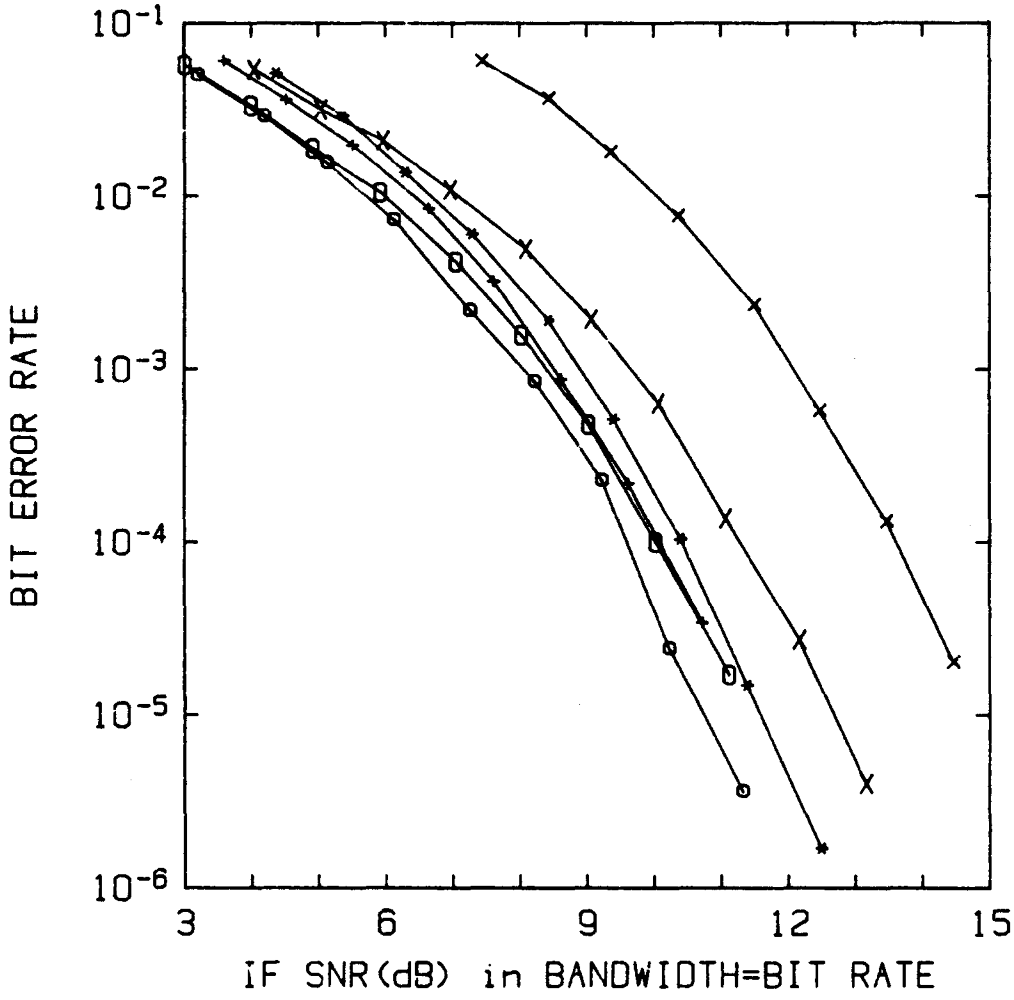

Figure 115. BER Comparison PCM/FM and PCM/PM.

Table 9. IF SNR for 10^{-4} BER for Various Modulation Methods.

PCM Code	Modulation Method	Modulation Peak Dev.	Bit Rate (kb/s)	PREMOD (kHz)	IF BW (kHz)	Bit DET	IF SNR in Bandwidth= Bit Rate for 10^{-4} BER
NRZ-L	FM	350	1000	None	1000	F/S	10.6
NRZ-L	FM	306	1000	None	1000	F/S	11.0
NRZ-L	FM	405	1000	None	1000	F/S	11.0
NRZ-L	FM	200	1000	700	1500	F/S	15.3
NRZ-L	FM	357	1000	700	1500	F/S	11.9
NRZ-L	FM	245	700	500	1000	F/S	11.5
NRZ-L	FM	123	700	500	1000	F/S	16.6
NRZ-L	FM	175	500	None	1000	F/S	12.4
NRZ-L	FM	178	500	350	500	F/S	10.4
NRZ-L	FM	178	500	350	1000	F/S	12.7
NRZ-L	FM	178	500	350	1500	F/S	13.7
BIO-L	FM	250	500	1000	1000	I/D	14.6
BIO-L	FM	325	500	1000	1000	I/D	13.5
BIO-L	FM	400	500	1000	1000	I/D	14.2
BIO-L	FM	250	500	700	1500	I/D	15.2
BIO-L	FM	325	500	700	1500	I/D	14.4
BIO-L	FM	400	500	700	1500	I/D	14.6
BIO-L	FM	325	500	500	1000	I/D	14.7
BIO-L	FM	325	500	700	1000	I/D	13.7
NRZ-M	PM	80	500	1000	3000	I/D	10.0
NRZ-M	PM	90	500	1000	3000	I/D	9.5
NRZ-M	PM	100	500	1000	3000	I/D	9.5
NRZ-M	PM	80	500	350	3000	I/D	11.0
NRZ-M	PM	90	500	350	3000	I/D	10.5
NRZ-M	PM	100	500	350	3000	I/D	10.3
NRZ-M	PM	90	500	1000	1000	I/D	9.9
BIO-L	PM	60	500	1000	4000	I/D	11.4
BIO-L	PM	75	500	1000	4000	I/D	10.0
BIO-L	PM	90	500	1000	4000	I/D	9.7
BIO-M	PM	90	500	1000	4000	I/D	10.0
BIO-L	PM	60	500	500	4000	I/D	13.1
BIO-L	PM	75	500	500	4000	I/D	11.8
BIO-L	PM	90	500	500	4000	I/D	10.9
BIO-M	PM	90	500	1000	4000	I/D	11.2
BIO-L	PM	75	500	500	1500	I/D	11.9
BIO-L	PM	75	500	1000	1500	I/D	10.7
BIO-L	PM	75	500	1000	1000	I/D	11.5
BIO-M	PM	90	500	1000	1000	I/D	11.4
BIO-M	PM	90	500	1000	1500	I/D	10.7

8. The best receiver IF bandwidths are:

NRZ PCM/FM	1 to 1.5 times the bit rate.
BIPHASE PCM/FM	2 to 3 times the bit rate.
NRZ or BIPHASE PCM/PM	As wide as possible (assuming no predetection recording).
Predetection recording	No wider than twice the predetection carrier frequency.

9. A filter and sample bit detector is usually best for NRZ PCM/FM and heavily-filtered NRZ PCM/PM. An integrate and dump bit detector is usually best for wideband NRZ PCM/PM.

10. NRZ PCM/FM has the narrowest spectral occupancy of the modulation methods discussed. The spectral occupancies of the various modulation methods are shown in table 10. In summary, the relative occupied bandwidths of the various methods are:

NRZ PCM/FM	1.
BIPHASE PCM/FM	2.4 to 3.2.
NRZ PCM/PM	1.6 to 3.2.
BIPHASE PCM/PM	3.2 to 6.4.

11. The maximum bit rate should be no greater than the predetection carrier frequency for NRZ signals and no greater than one-half the predetection carrier frequency for biphase signals.

12. Upconversion and demodulation always yields BERs which are as good as or better than the BERs which result from demodulation at tape carrier frequencies (proper IF bandwidths assumed).

Table 10. Occupied Bandwidths for Various Modulation Methods.

Modulation		Bit Rate	Premodulation Filter (CD)	Peak	Occupied
Code	Method	(kb/s)	Bandwidth (kHz)	Deviation (kHz or Deg.)	Bandwidth (kHz)
NRZ-L	FM	800	800	285	2040
NRZ-L	FM	800	400	285	2010
BIO-L	FM	400	800	260	3200
BIO-L	FM	400	400	260	2400
NRZ-M	PM	800	800	90	6400
NRZ-M	PM	800	400	90	3200
BIO-L	PM	400	800	75	4800
BIO-L	PM	400	400	75	3200
BIO-M	PM	400	800	90	6400
BIO-M	PM	400	400	90	3200

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5. Cartier, D. E. "Limiter-Discriminator Detection Performance of Manchester and NRZ Coded FSK," in IEEE Transactions of Aerospace and Electronic Systems, Vol. AES-13, pp. 62-70, January 1977.

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APPENDIX A
FREQUENCY MODULATION NOISE CHARACTERISTICS

The two major types of noise signals present at the output of a frequency modulation (FM) demodulator are commonly called fluctuation noise and pop or click noise.[A1,A2,A3] Fluctuation noise is defined as the error in the demodulated output caused by a noise vector being summed with the signal vector where the instantaneous noise amplitude is smaller than the signal amplitude. Pop noise is defined as the error in the demodulated output which occurs when the instantaneous vector sum of the signal plus noise encircles the origin (the noise amplitude has to be equal to or greater than the signal amplitude for this to occur).

A vector diagram illustrating fluctuation noise is presented in figure A-1. The amplitude of the noise is 20% of the amplitude of the signal in figure A-1. This limits the time rate of change of the angle ϕ which is the FM demodulator output error signal (the signal vector is assumed to be stationary and the noise vector rotates with respect to the signal vector in this model). If we further assume that the instantaneous frequency of the noise is 400 kHz lower than the signal frequency, we can plot the vector sum and the demodulator error as a function of time. Figure A-2 presents the sum of a signal with amplitude of 1 at a frequency of 10 MHz, and noise with an amplitude of 0.2 with a frequency of 9.6 MHz. The dots show the signal with no noise. The initial and final vector relationship is as shown in figure A-1. Figure A-3 shows the demodulator error signal for these conditions. In the real-world, the amplitude, phase, and frequency of the noise are random variables. The largest error is slightly larger than +100 kHz and occurs when the vectors are antiparallel. The mean value of the error is zero. Fluctuation noise dominates at high IF signal-to-noise

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[A-1] Crosby, M. G. Frequency Modulation Noise Characteristics. Proc. IRE, 25, 472-514 (1937).

[A-2] Stumpers, F. L. H. M. Theory of Frequency-Modulation Noise. Proc. IRE, 36, 1081-1092 (1948).

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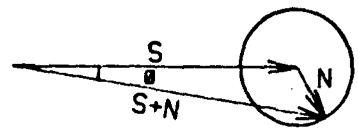

Figure A-1. Fluctuation Noise Vector Diagram for N=0.2S.

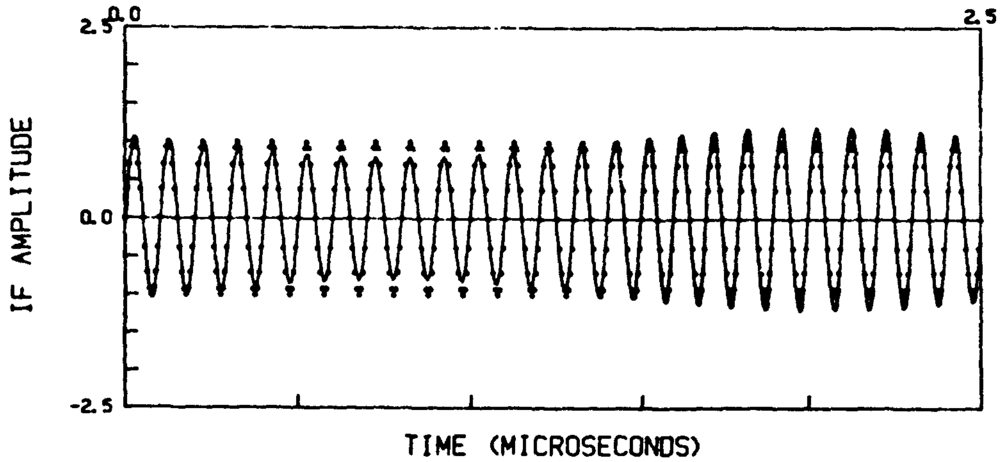

Figure A-2. IF Amplitude for N=0.2S.

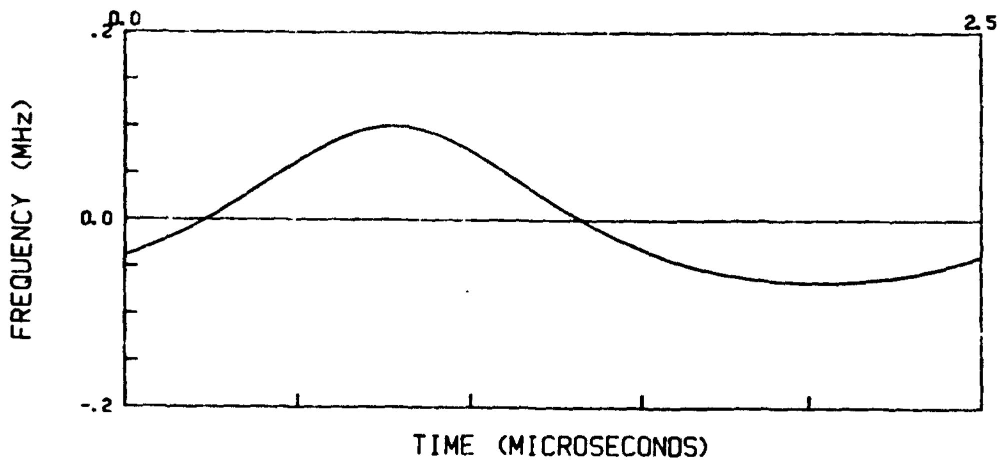

Figure A-3. Demodulator Output for N=0.2S.

ratios (SNRs), that is, above approximately 12 dB. Fluctuation noise is characterized as having a Gaussian amplitude distribution and a power spectrum proportional to:

$$\frac{f^2 N_O(f)}{A_C^2}$$

where: f = frequency of the noise
$N_O(f)$ = noise power spectral density at input to demodulator
A_C = amplitude of the signal

Therefore, the fluctuation noise at the output of the demodulator increases at 6 dB per octave when $N_O(f)$ is constant, assuming no video filter. The frequency response characteristic of the IF filter is the main factor which shapes $N_O(f)$. Examples of typical IF filter bandpass characteristics are shown in figures A-4, A-5 and A-6. A time domain plot of fluctuation noise is shown in figure A-7 and a spectral plot is shown in figure A-8.

Pop noise occurs when the instantaneous vector sum of the signal plus noise encircles the origin causing a rapid change of $\pm 2\pi$ radians in the angle $\phi(t)$. This is illustrated in figure A-9. The signal amplitude in figure A-9 is 1 while the instantaneous noise amplitude is 1.1. If we define the signal frequency to be 10 MHz and the instantaneous noise frequency to be 9.6 MHz, we can generate a time record of the IF amplitude for one cycle of ϕ. This is shown in figure A-10. Note that almost a full cycle, approximately 83% of a cycle, of the 10-MHz signal (represented by dots) occurs between zero crossings of the vector sum of the signal plus noise when the amplitude of the signal plus noise is at a minimum. This causes the large pulse shown in figure A-11. The energy contained in the center of the spike (0.34 microsecond duration) is π radians or 1/2 cycle. The signals shown in A-10 and A-11 do not include any effects due to IF bandpass filtering or video filtering. The effect of these filters would be to slow down the time rate of change of the demodulated output and reduce the total energy. Figures A-12 and A-13 show an actual noise "pop" and the corresponding linear IF signal. The test conditions included a 1-MHz IF bandwidth and 500 kHz/volt demodulator sensitivity for both figures. The video bandwidth was 1 MHz for figure A-12 and 500 kHz for figure A-13. The sudden change in $\phi(t)$ causes a narrow pulse with an area of approximately $\pm 2\pi$ radians to be generated. This is the same amount of energy as would be contained in an unfiltered PCM/FM bit with a peak deviation equal to the bit rate. The noise pops are usually in the direction to cause bit errors in PCM/FM. The reason is that the average frequency of the noise is usually near the center frequency of the IF filter. Therefore, when the carrier is deviated to a frequency which is higher than the center frequency, the instantaneous noise frequency will usually be lower than the signal frequency. This causes the pops to be in the direction towards the center frequency. This is illustrated in figures A-14 and A-15. Therefore, each pop will usually cause a bit error for PCM/FM with a peak deviation less than the bit rate. Figure A-16 shows a noise pop that is in the direction away from the center frequency. The noise can also capture the demodulator for a long enough time to cause multiple cycles of $\phi(t)$. This is especially likely when the carrier is deviated away from the center frequency. This causes a noise pop with area approximately equal to the number of cycles of

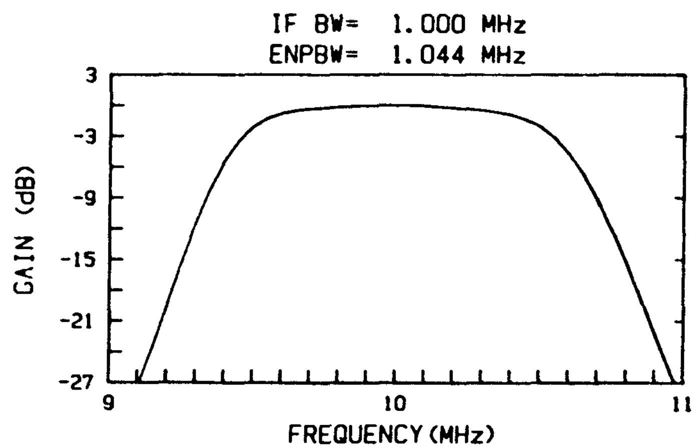

Figure A-4. IF Filter Frequency Response (Filter A).

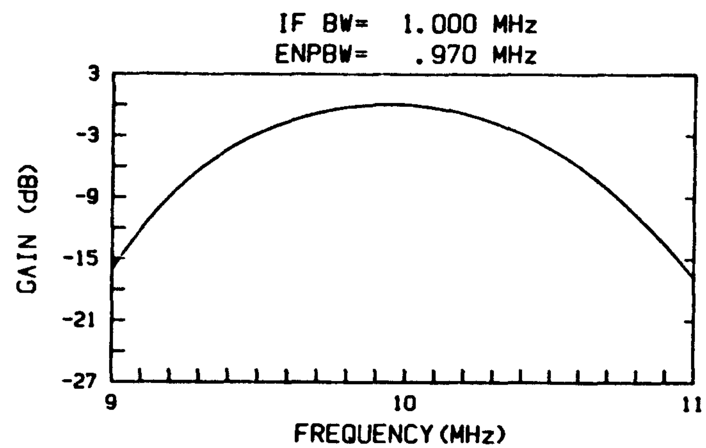

Figure A-5. IF Filter Frequency Response (Filter B).

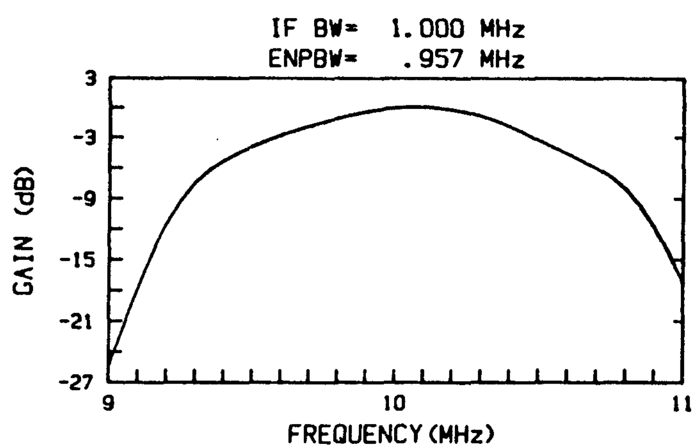

Figure A-6. IF Filter Frequency Response (Filter C).

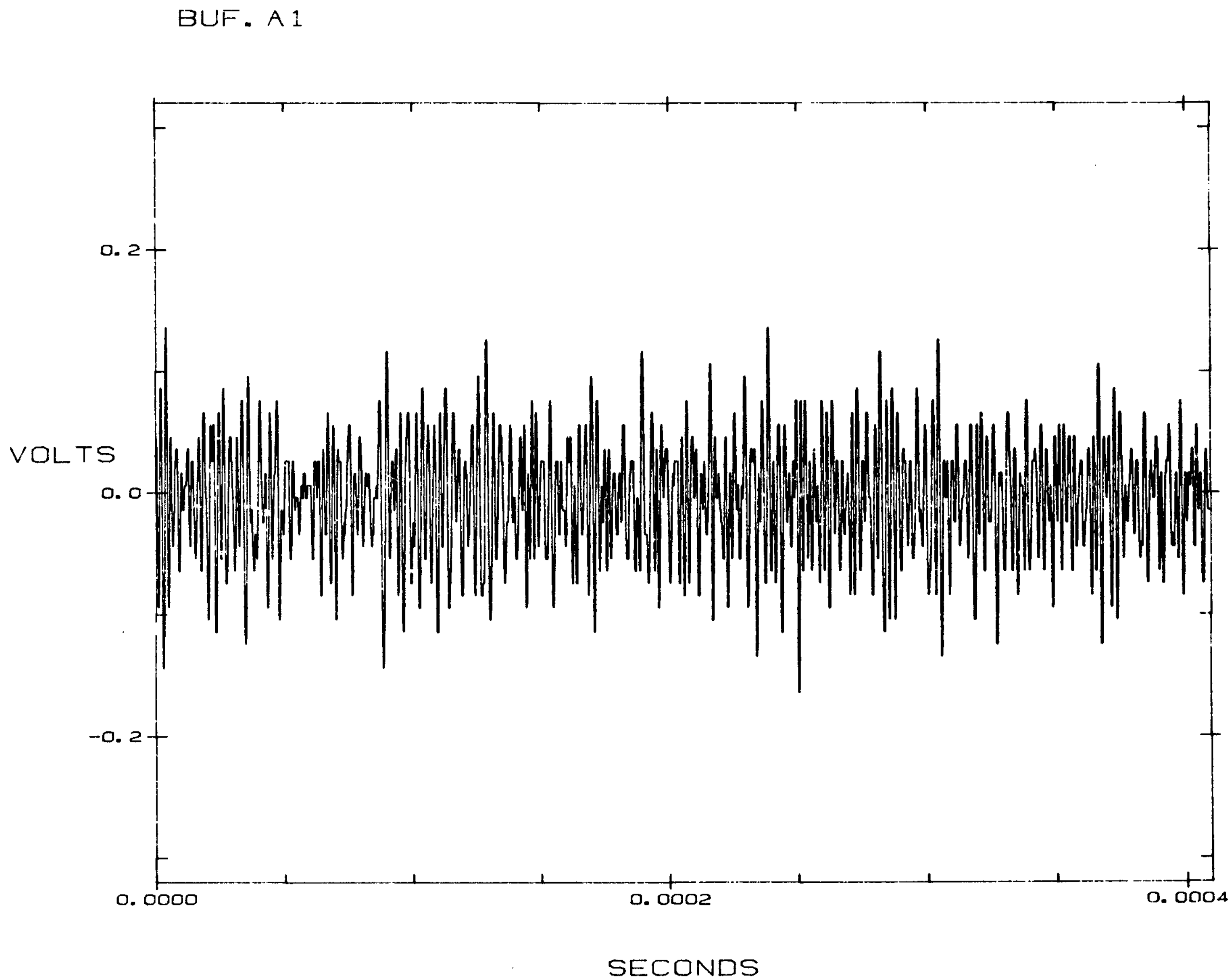

Figure A-7. Fluctuation Noise.

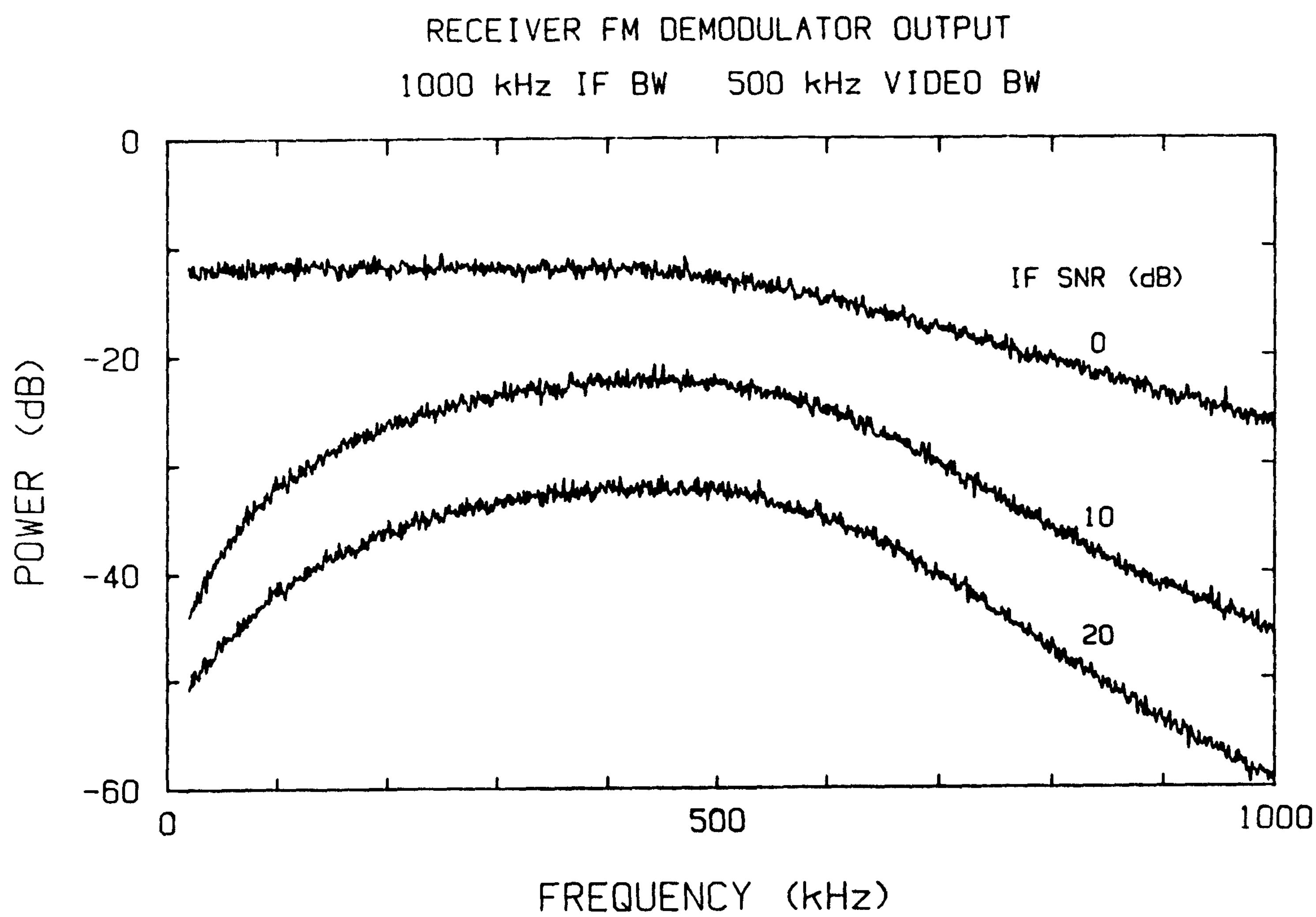

Figure A-8. Receiver Video Noise Power Spectral Density.

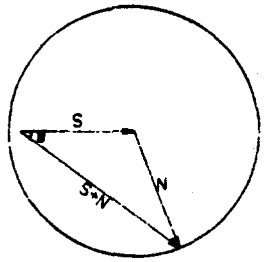

Figure A-9. Vector Diagram of Pop Noise (N=1.1S).

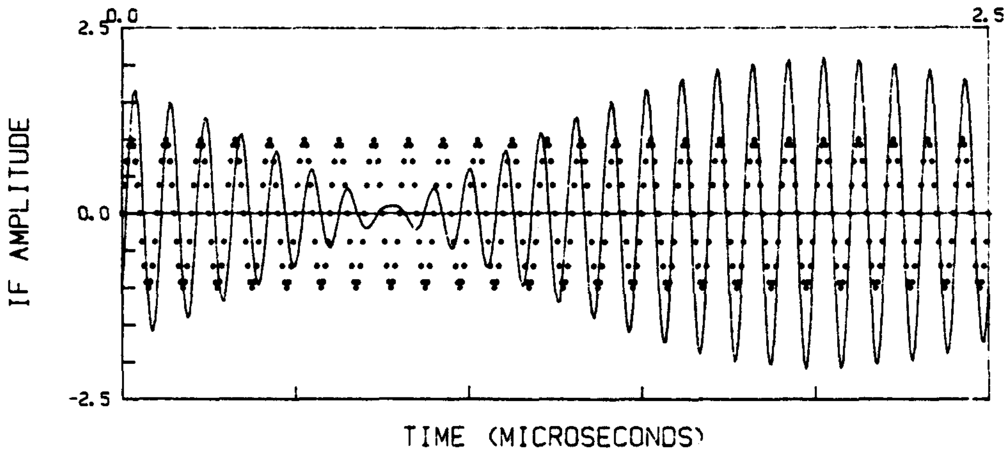

Figure A-10. IF Amplitude (N=1.1S).

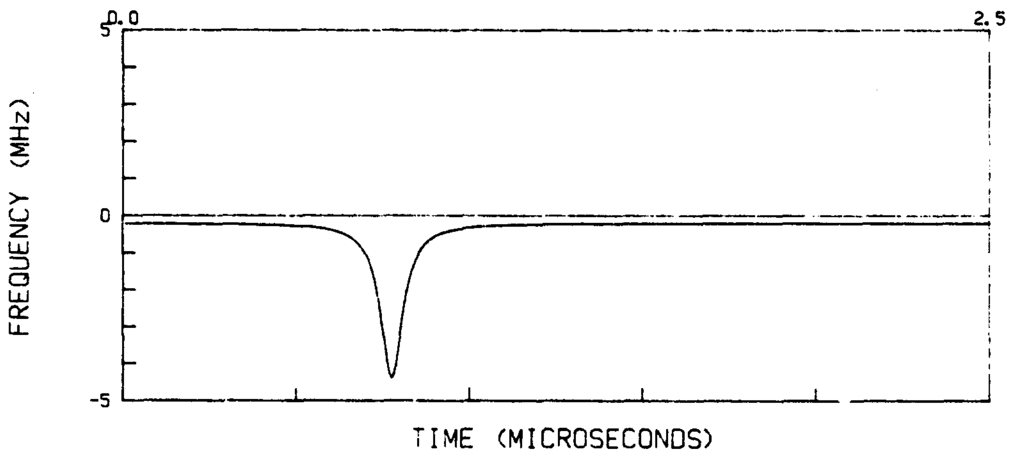

Figure A-11. Demodulator Output (N=1.1S).

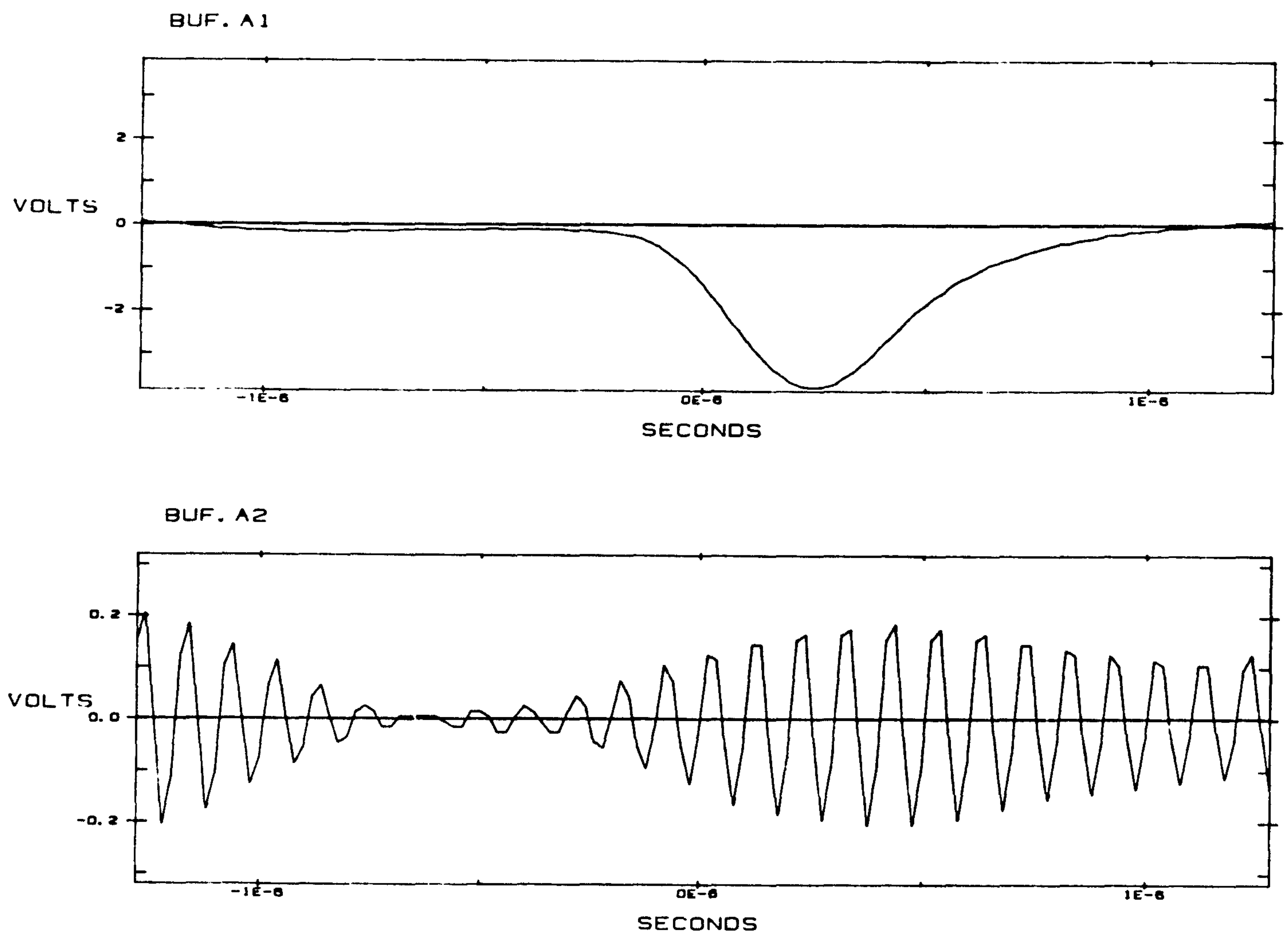

Figure A-12. Pop Noise (Upper Trace Video BW=1 MHz) and IF Signal.

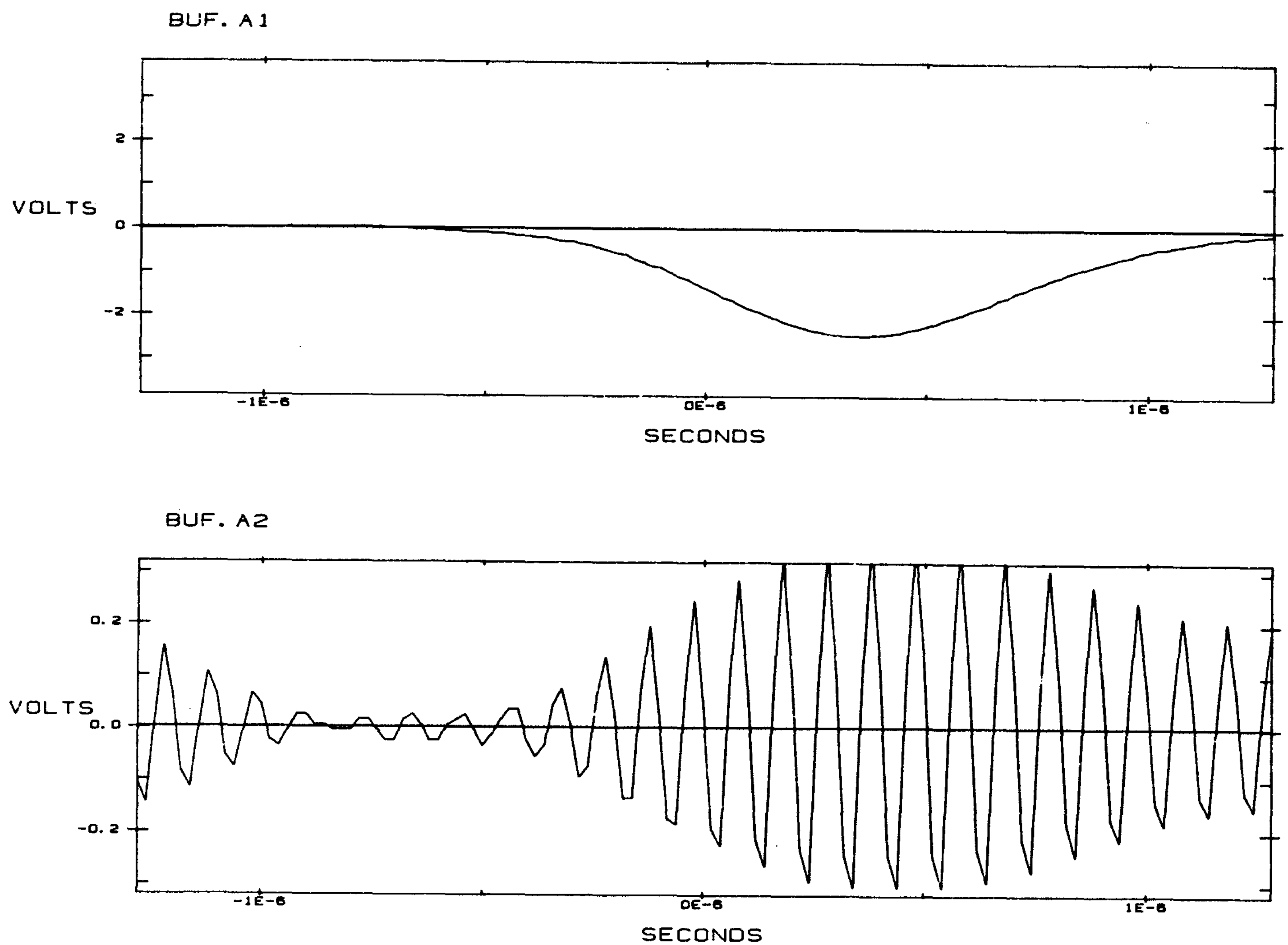

Figure A-13. Pop Noise (Upper Trace Video BW=0.5 MHz) and IF Signal.

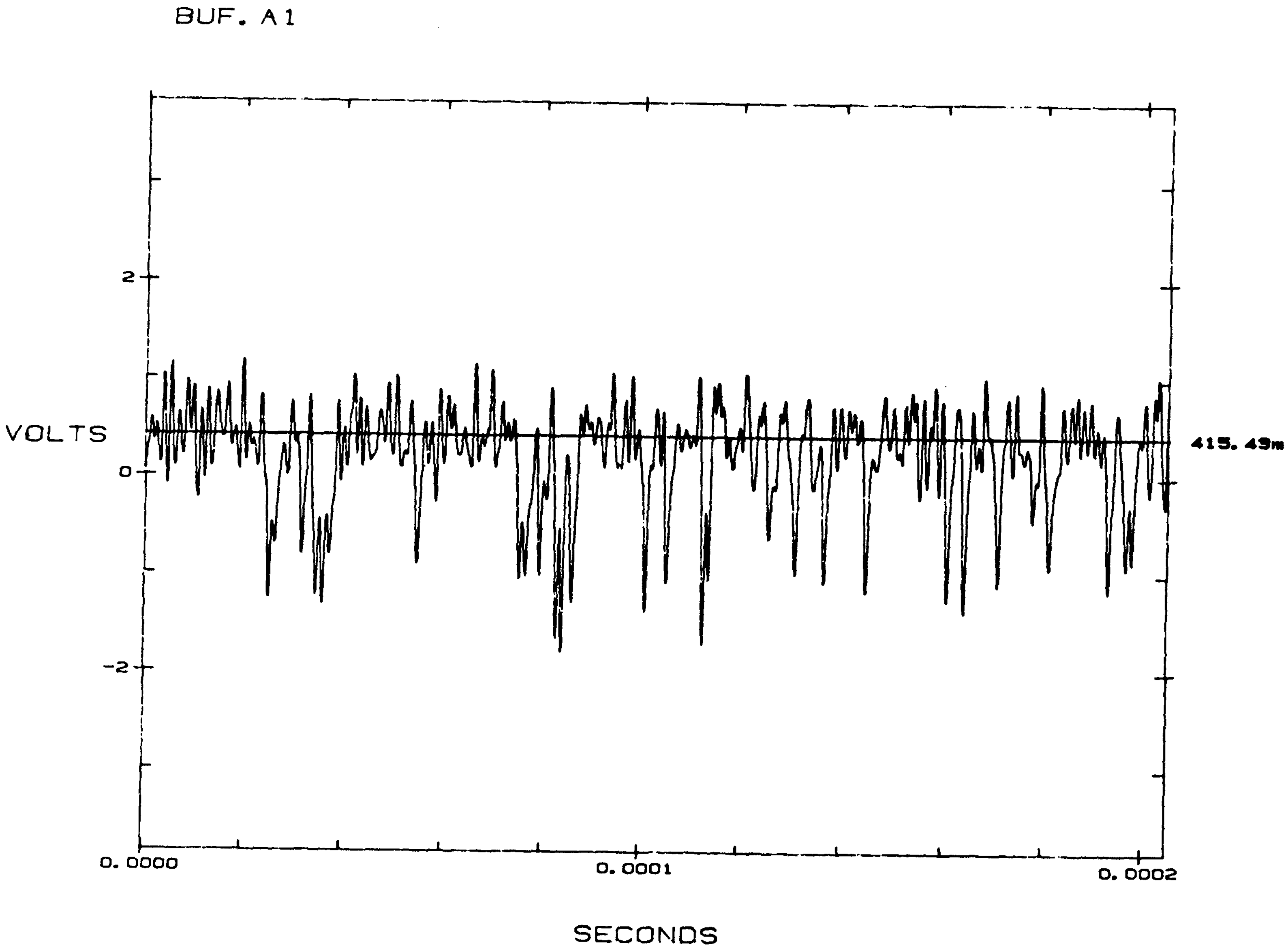

Figure A-14. Pop Noise IF Frequency=10.25 MHz.

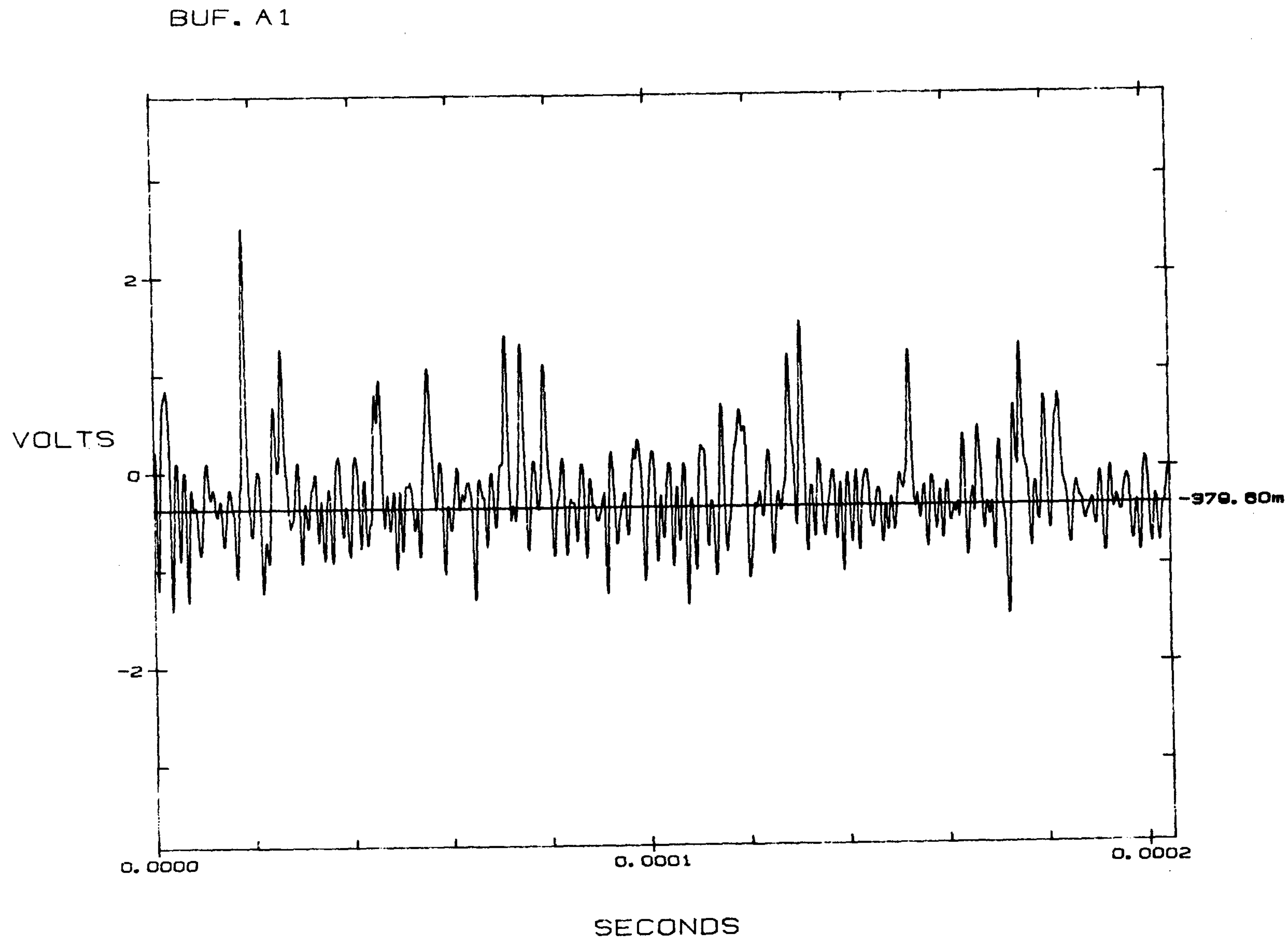

Figure A-15. Pop Noise IF Frequency=9.75 MHz.

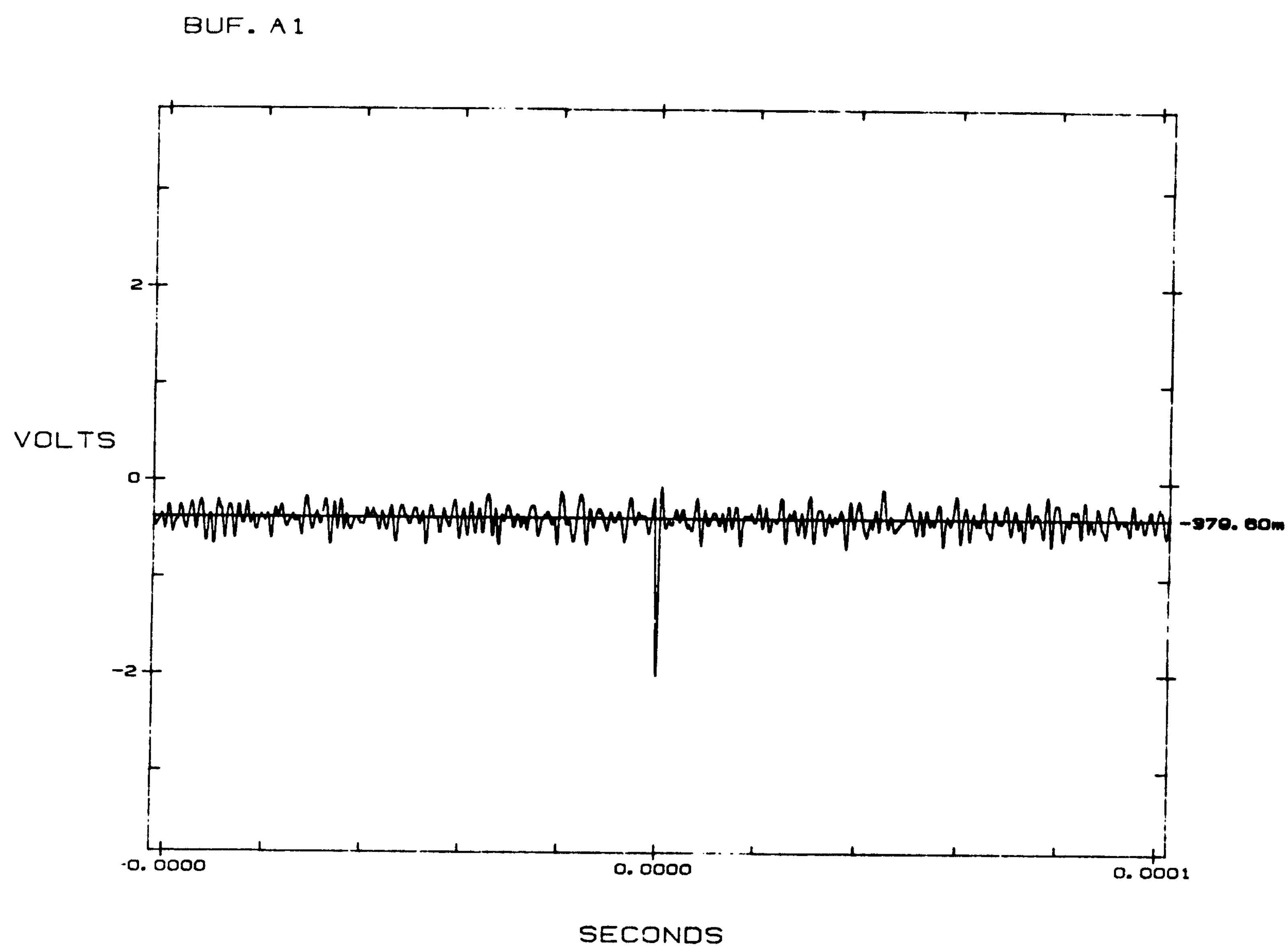

Figure A-16. Pop Noise Away from Center Frequency.

$\phi(t)$. The FM demodulator output with a center frequency input was 0 volt DC and the demodulator sensitivity was 625 kHz/volt for figures A-13 through A-19. Figures A-17 and A-18 show the differences that occur in pop amplitude. The variation in pop amplitude is further illustrated by the superposition of several pops in figures A-19 and A-20. The test conditions for figure A-19 were: IF SNR = 10 dB, IF bandwidth = 1 MHz, video bandwidth = 500 kHz, and RF input frequency = center frequency -250 kHz. The amplitude of the pops varies greatly. The test conditions for figures A-20 and A-21 were: IF SNR = 10 dB, IF bandwidth = 10 MHz, video bandwidth = 6 MHz, demodulator sensitivity = 4 MHz/volt, and RF input frequency = center frequency. The area of all non-doublet pops was approximately 1 cycle under these conditions. Doublet pops are shown in figures A-21 and A-22. Doublets occur when the noise does not capture the demodulator for a long enough time to complete a $\pm 2\pi$ swing of $\phi(t)$. Doublets have an area of approximately 0.

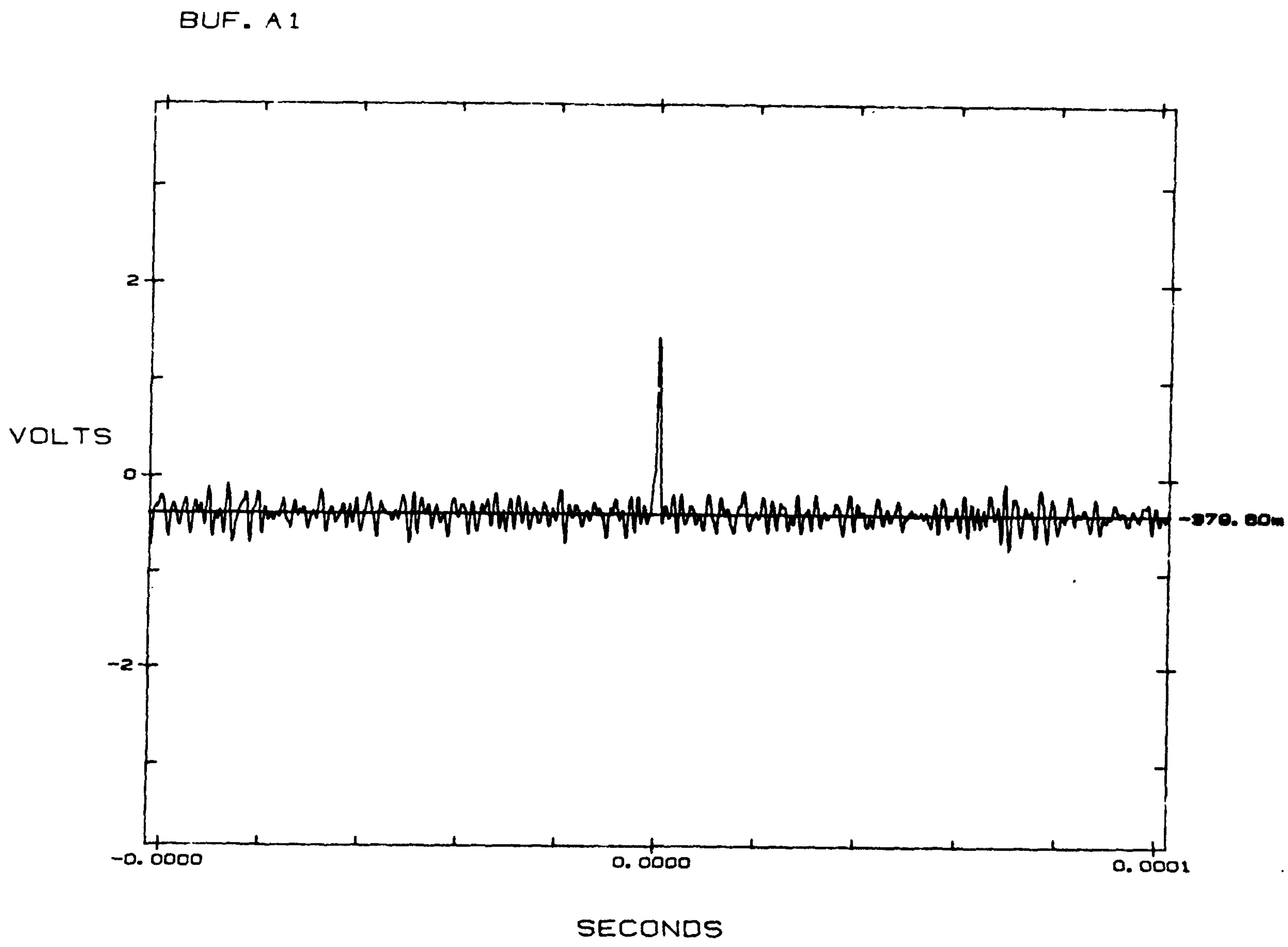

Figure A-17. Noise Pop with Area 2 PI.

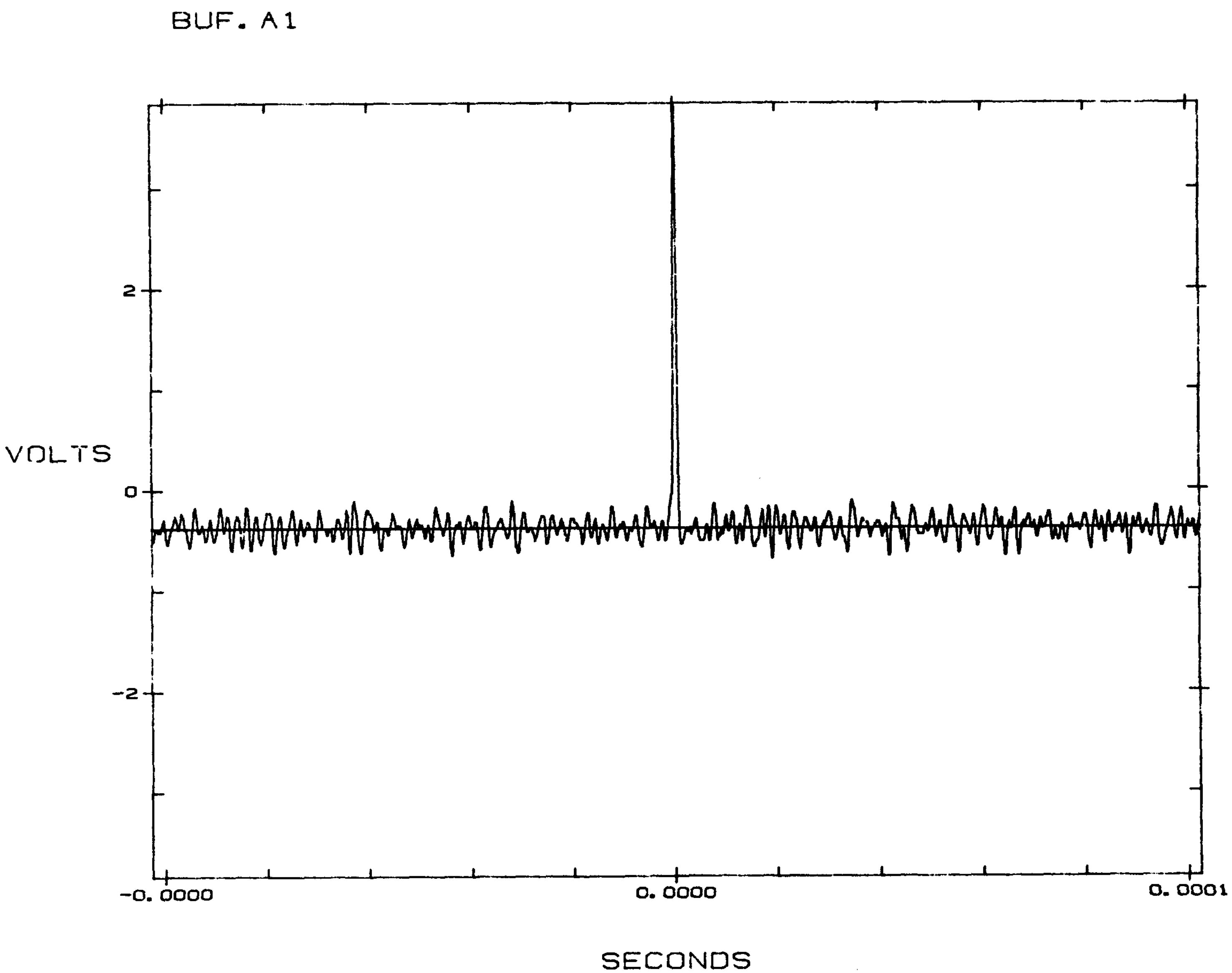

Figure A-18. Noise Pop with Area >2 PI.

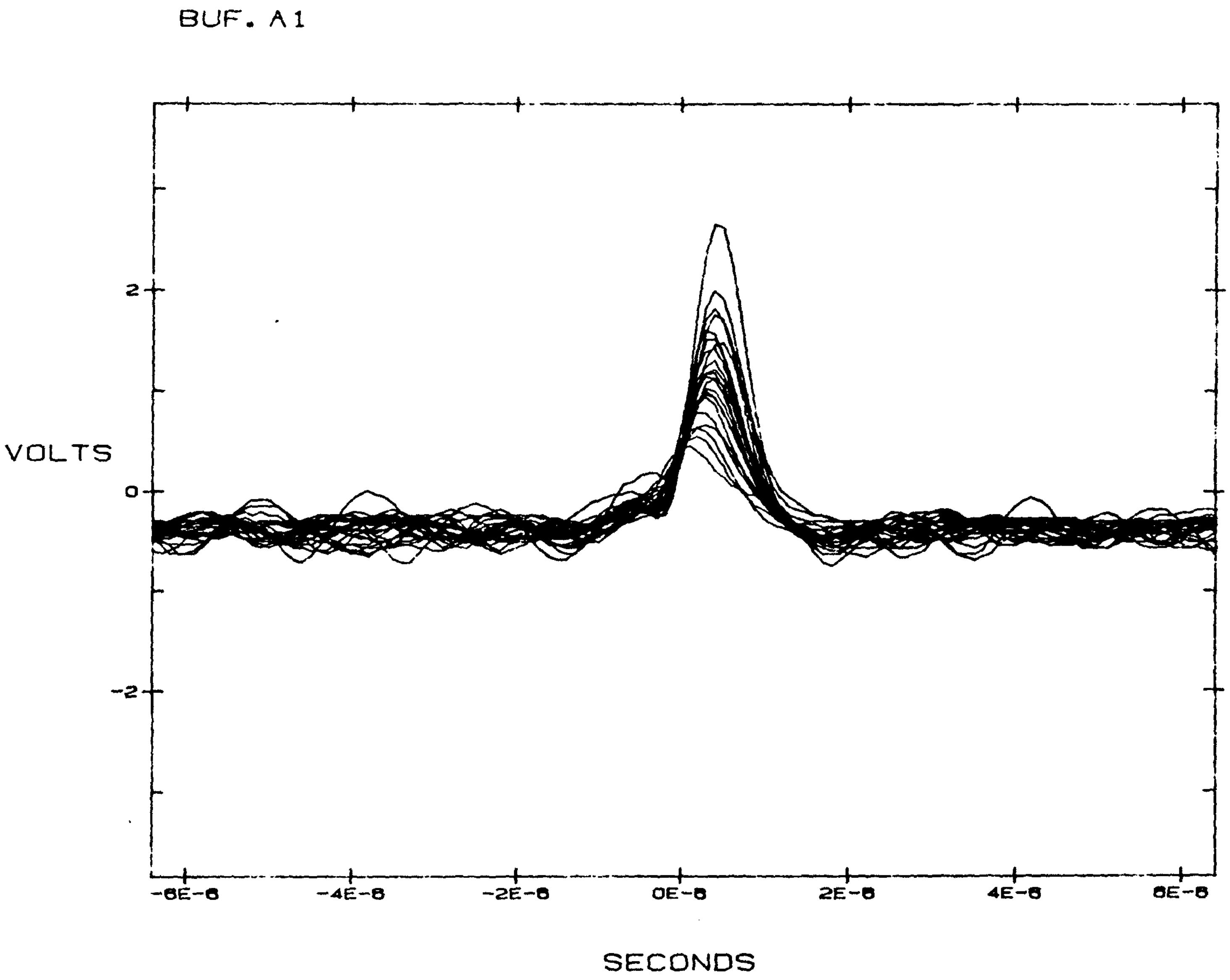

Figure A-19. Superposition of Several Noise Pops (IF BW=1 MHz).

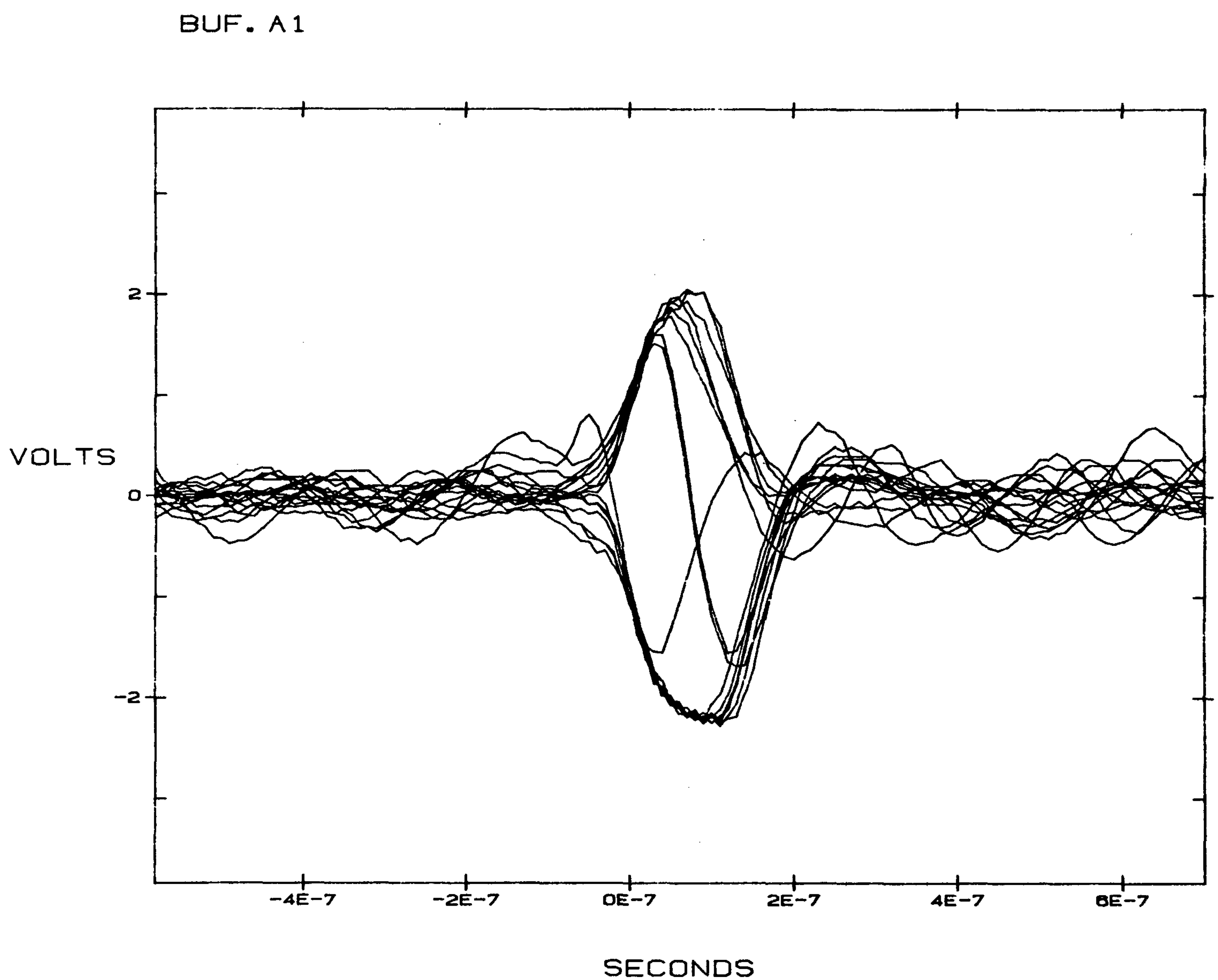

Figure A-20. Superposition of Several Noise Pops (IF BW=10 MHz).

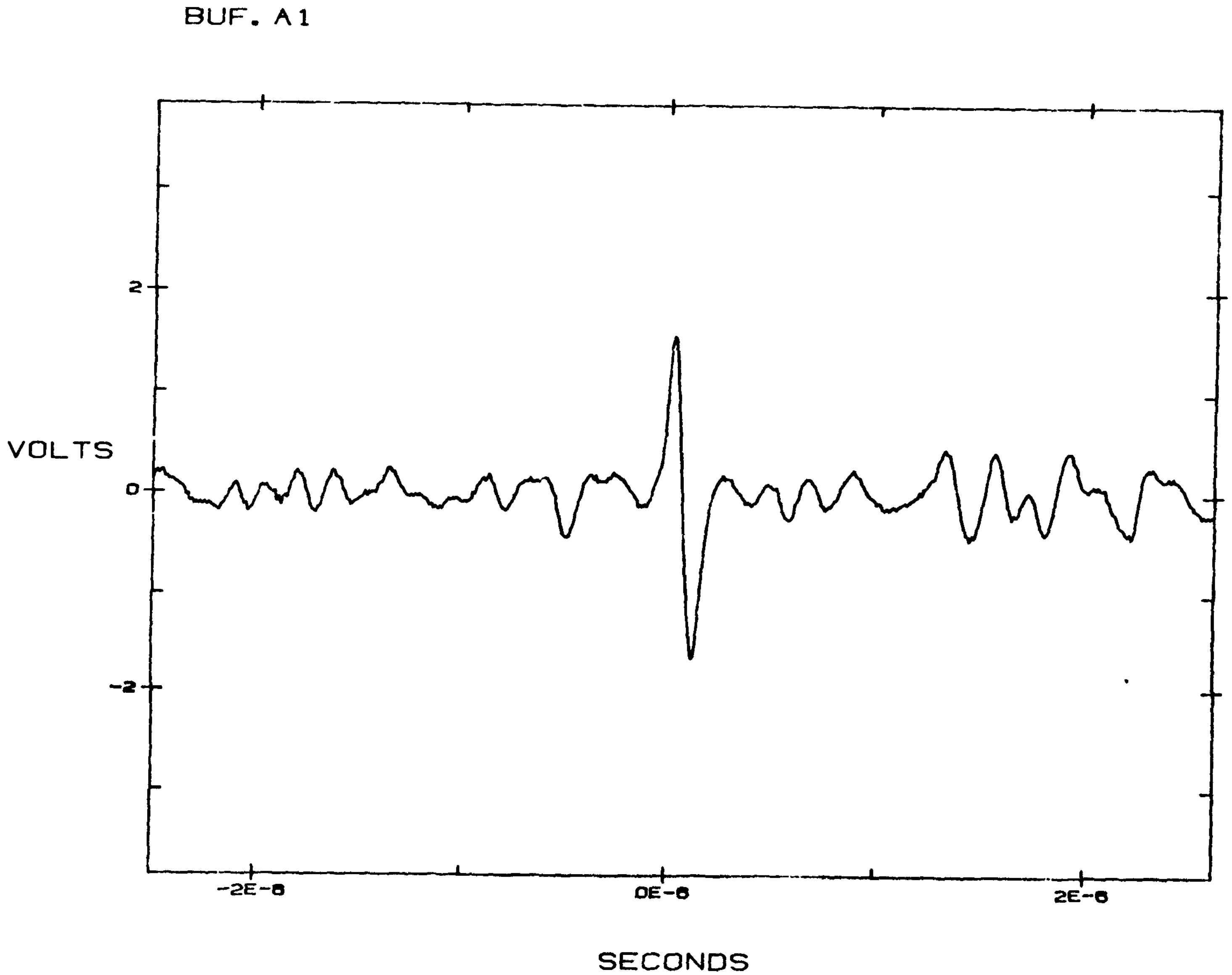

Figure A-21. Doublet Noise.

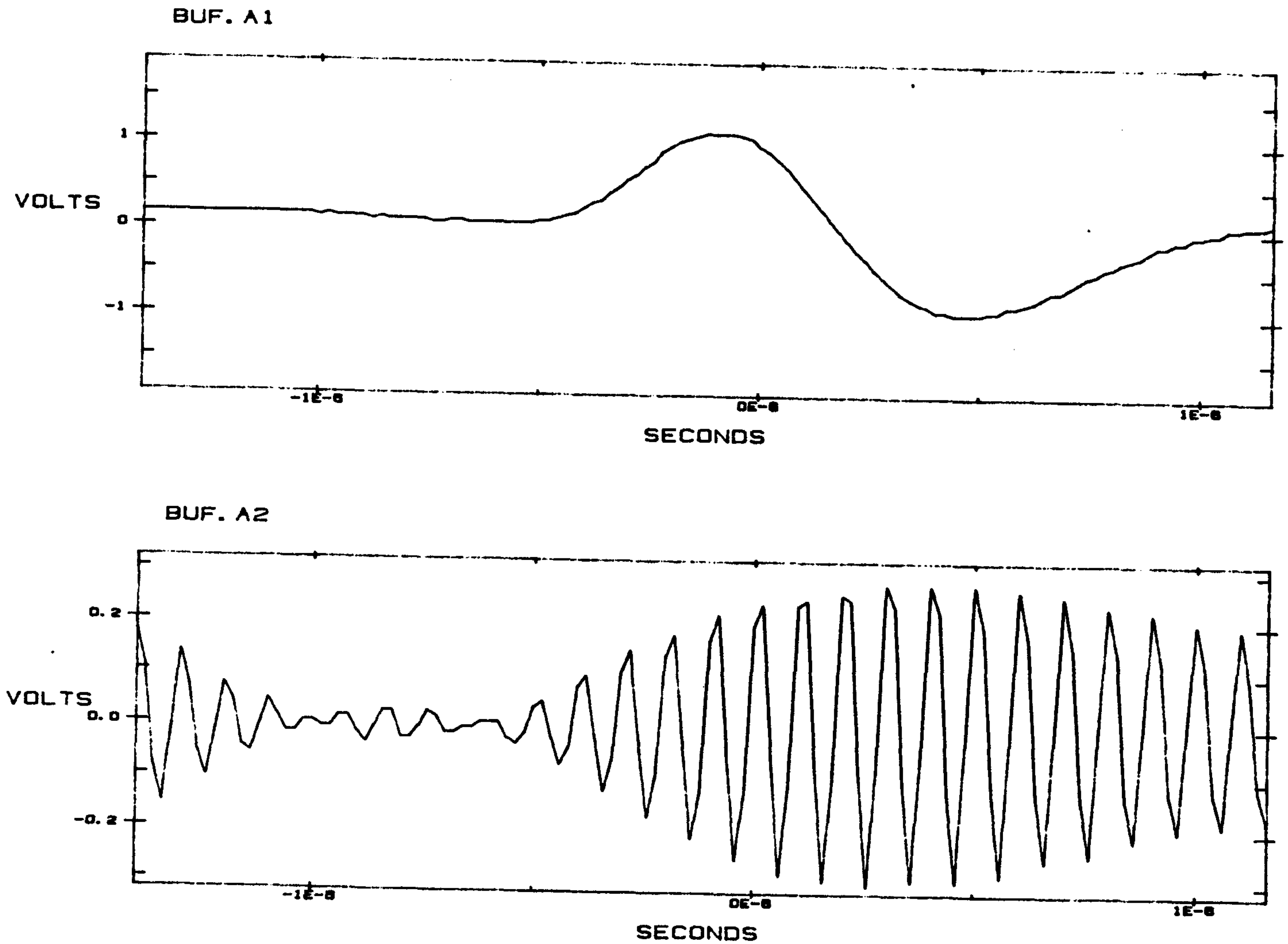

Figure A-22. Doublet Noise (Upper Trace) and IF Signal.

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